IEC 62232

Edition 3.0 2022-10

INTERNATIONAL STANDARD

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Determination of RF field strength, power density and SAR in the vicinity of base stations for the purpose of evaluating human exposure

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IEC 62232:2022-10(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 13.280; 17.240

ISBN 978-2-8322-5778-4

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CONTENTS

FOREWORD 16
INTRODUCTION 18
1 Scope 19
2 Normative references 20
3 Terms and definitions 21
4 Symbols and abbreviated terms 36
4.1 Physical quantities 36
4.2 Constants 36
4.3 Abbreviated terms 36
5 How to use this document 39
5.1 Quick start guide 39
5.2 RF evaluation purpose categories 42
5.3 Implementation case studies 42
6 Evaluation processes for product compliance, product installation compliance and in-situ RF exposure assessments 42
6.1 Evaluation process for product compliance 42
6.1.1 General 42
6.1.2 Establishing compliance boundaries 42
6.1.3 Iso-surface compliance boundary definition 43
6.1.4 Simple compliance boundaries 43
6.1.5 Methods for establishing the compliance boundary 45
6.1.6 Uncertainty 49
6.1.7 Reporting for product compliance 49
6.2 Evaluation process used for product installation compliance 50
6.2.1 General 50
6.2.2 General evaluation procedure for product installations 50
6.2.3 Product installation compliance based on the actual maximum transmitted power or EIRP 52
6.2.4 Product installation data collection 55
6.2.5 Simplified product installation evaluation process 56
6.2.6 Assessment area selection 59
6.2.7 Measurements 60
6.2.8 Computations 62
6.2.9 Uncertainty 62
6.2.10 Reporting for product installation compliance 63
6.3 In-situ RF exposure evaluation or assessment process 64
6.3.1 General 64
6.3.2 In-situ measurement process 64
6.3.3 Site analysis 65
6.3.4 Case A evaluation 66
6.3.5 Case B evaluation 66
6.3.6 Uncertainty 67
6.3.7 Reporting 67
6.4 Averaging procedures 67
6.4.1 Spatial averaging 67
6.4.2 Time averaging 68
7 Determining the evaluation method 68

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7.1 Overview 68
7.2 Process to determine the evaluation method 68
7.2.1 General 68
7.2.2 Establishing the evaluation points in relation to the source-environment plane 69
7.2.3 Exposure metric selection 70
8 Evaluation methods 71
8.1 General 71
8.2 Measurement methods 72
8.2.1 General 72
8.2.2 RF field strength and power density measurements 72
8.2.3 SAR measurements 73
8.3 Computation methods 74
8.4 Methods for assessment based on actual maximum approach 76
8.4.1 General requirements 76
8.4.2 Actual transmitted power or EIRP monitoring 76
8.4.3 Actual transmitted power or EIRP control 77
8.5 Methods for the assessment of RF exposure to multiple sources 78
8.6 Methods for establishing the BS transmitted power or EIRP 79
9 Uncertainty 80
10 Reporting 80
10.1 General requirements 80
10.2 Report format 81
10.3 Opinions and interpretations 82
Annex A (informative) Source-environment plane and guidance on the evaluation method selection 83
A.1 Guidance on the source-environment plane 83
A.1.1 General 83
A.1.2 Source-environment plane example 83
A.1.3 Source regions 84
A.2 Select between computation or measurement approaches 90
A.3 Select measurement method 91
A.3.1 Selection stages 91
A.3.2 Selecting between RF field strength, power density and SAR measurement approaches 91
A.3.3 Selecting between broadband and frequency selective measurement 92
A.3.4 Selecting RF field strength measurement procedures 93
A.4 Select computation method 93
A.5 Additional considerations 95
A.5.1 Simplicity 95
A.5.2 Evaluation method ranking 95
A.5.3 Applying multiple methods for RF exposure evaluation 95
Annex B (normative) Evaluation methods 96
B.1 Overview 96
B.2 General 96
B.2.1 Coordinate systems and reference points 96
B.2.2 Variables 97
B.3 RF exposure evaluation principles 98
B.3.1 Simple calculation of RF field strength and power density 98

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B.3.2 Measurement of RF field strength and power density 102
B.3.3 Spatial averaging 104
B.3.4 Time averaging 107
B.3.5 Comparing measured and computed values 109
B.3.6 Personal RF monitors 109
B.4 RF field strength and power density measurements 109
B.4.1 Applicability of RF field strength and power density measurements 109
B.4.2 In-situ RF exposure measurements 109
B.4.3 Laboratory based RF field strength and power density measurements 121
B.4.4 RF field strength and power density measurement uncertainty 131
B.5 SAR measurements 136
B.5.1 Overview of SAR measurements 136
B.5.2 SAR measurement requirements 136
B.5.3 SAR measurement description 138
B.5.4 SAR measurement uncertainty 143
B.6 Basic computation methods 146
B.6.1 General 146
B.6.2 Basic computation formulas for RF field strength or power density evaluation 146
B.6.3 Basic whole-body SAR and peak spatial-average SAR evaluation formulas 153
B.6.4 Basic compliance boundary assessment method for BS using parabolic dish antennas 160
B.6.5 Basic compliance boundary assessment method for intentionally radiating cables 163
B.7 Advanced computation methods 164
B.7.1 General 164
B.7.2 Synthetic model and ray tracing algorithms 164
B.7.3 Full wave RF exposure computation 171
B.7.4 Full wave SAR computation 180
B.8 Extrapolation from the evaluated values to the maximum or actual values 185
B.8.1 Extrapolation method 185
B.8.2 Extrapolation to maximum in-situ RF field strength or power density using broadband measurements 187
B.8.3 Extrapolation to maximum in-situ RF field strength / power density using frequency or code selective measurements 187
B.8.4 Influence of traffic in real operating network 188
B.8.5 Extrapolation for massive MIMO and beamforming BS 189
B.8.6 Maximum exposure extrapolation with dynamic spectrum sharing (DSS) 191
B.9 Guidance for implementing the actual maximum approach 192
B.9.1 BS actual EIRP evaluation assumptions 192
B.9.2 Technology duty-cycle factor description 193
B.9.3 CDF evaluation using modelling studies 195
B.9.4 CDF evaluation using measurement studies on operational BS sites 196
B.9.5 Actual transmitted power or EIRP monitoring counters 198
B.9.6 Configurations with multiple transmitters 198
B.10 Transmitted power or EIRP evaluation 200
B.10.1 General 200
B.10.2 Measurement of the transmitted power in conducted mode 200
B.10.3 Measurement of the transmitted power in OTA conditions 201

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B.10.4 Measurement of the EIRP in OTA and laboratory conditions 201
B.10.5 Measurement of the EIRP in OTA and in-situ conditions 202
Annex C (informative) Guidelines for the validation of power or EIRP control features and monitoring counter(s) related to the actual maximum approach 203
C.1 Overview 203
C.2 Guidelines for validating control feature(s) and monitoring counters 203
C.3 Validation of power or EIRP monitoring counter in laboratory conditions 204
C.3.1 Validation of power or EIRP monitoring counter in conducted mode – test procedure 204
C.3.2 Validation of power or EIRP monitoring counter in OTA mode – test procedure 206
C.3.3 Validation of control feature(s) in laboratory conditions 209
C.3.4 Validation of control features using in-situ measurements 212
C.4 Validation test report 214
C.5 Case studies 215
C.5.1 Case study A – In-situ validation 215
C.5.2 Case study B – In-situ validation 219
C.5.3 Case study C – In-situ validation 222
Annex D (informative) Rationale supporting simplified product installation criteria 227
D.1 General 227
D.2 Class E2 227
D.3 Class E10 228
D.4 Class E100 229
D.5 Class E+ 231
D.6 Simplified formulas for millimetre-wave antennas using massive MIMO or beam steering 232
Annex E (informative) Technology-specific exposure evaluation guidance 234
E.1 Overview to guidance on specific technologies 234
E.2 Summary of technology-specific information 234
E.3 Guidance on spectrum analyser settings 235
E.3.1 Overview of spectrum analyser settings 235
E.3.2 Detection algorithms 236
E.3.3 Resolution bandwidth and channel power processing 236
E.3.4 Integration per service 239
E.4 Stable transmitted power signals 239
E.4.1 TDMA/FDMA technology 239
E.4.2 WCDMA/UMTS technology 240
E.4.3 OFDM technology 241
E.5 WCDMA measurement and calibration using a code domain analyser 241
E.5.1 WCDMA measurements – General 241
E.5.2 WCDMA decoder characteristics 241
E.5.3 Calibration 242
E.6 Wi-Fi measurements 244
E.6.1 General 244
E.6.2 Integration time for reproducible measurements 245
E.6.3 Channel occupation 245
E.6.4 Some considerations 246
E.6.5 Measurement configuration and steps 246
E.6.6 Influence of the application layers 247

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E.6.7 Power control 247
E.7 LTE measurements 248
E.7.1 Overview 248
E.7.2 LTE transmission modes 248
E.7.3 LTE-FDD frame structure 249
E.7.4 LTE-TDD frame structure 250
E.7.5 Maximum LTE exposure evaluation 252
E.7.6 Instantaneous LTE exposure evaluation 257
E.7.7 MIMO multiplexing of LTE BS 258
E.8 NR BS measurements 258
E.8.1 General 258
E.8.2 Maximum NR exposure evaluation 258
E.9 Establishing compliance boundaries using numerical simulations of MIMO array antennas emitting correlated waveforms 268
E.9.1 General 268
E.9.2 Field combining near base stations for correlated exposure with the purpose of establishing compliance boundaries 268
E.9.3 Numerical simulations of MIMO array antennas with densely packed columns 269
E.9.4 Numerical simulations of large MIMO array antennas 270
E.10 Massive MIMO antennas 270
E.10.1 Overview 270
E.10.2 Deterministic conservative approach 270
E.10.3 Statistical conservative approach 270
E.10.4 Example approaches 271
Annex F (informative) Guidelines for the assessment of BS compliance with ICNIRP-2020 brief exposure limits 288
F.1 General 288
F.2 Brief exposure limits 288
F.3 Implications of brief exposure limits on signal modulation and TDD duty cycle 290
F.4 Implications of brief exposure limits on the actual maximum approach 290
Annex G (informative) Uncertainty 294
G.1 Background 294
G.2 Requirement to estimate uncertainty 294
G.3 How to estimate uncertainty 295
G.4 Guidance on uncertainty and assessment schemes 295
G.4.1 General 295
G.4.2 Overview of assessment schemes 295
G.4.3 Examples of assessment schemes 296
G.4.4 Assessment schemes and compliance probabilities 299
G.5 Guidance on uncertainty 301
G.5.1 Overview 301
G.5.2 Measurement uncertainty and confidence levels 302
G.6 Applying uncertainty for compliance assessments 303
G.7 Example influence quantities for field measurements 304
G.7.1 General 304
G.7.2 Calibration uncertainty of measurement antenna or field probe 304
G.7.3 Frequency response of the measurement antenna or field probe 304
G.7.4 Isotropy of the measurement antenna or field probe 306

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G.7.5 Frequency response of the spectrum analyser 306
G.7.6 Temperature response of a broadband field probe 306
G.7.7 Linearity deviation of a broadband field probe 307
G.7.8 Mismatch uncertainty 307
G.7.9 Deviation of the experimental source from numerical source 307
G.7.10 Meter fluctuation uncertainty for time-varying signals 307
G.7.11 Uncertainty due to power variation in the RF source 308
G.7.12 Uncertainty due to field gradients 308
G.7.13 Mutual coupling between measurement antenna or isotropic probe and object 309
G.7.14 Uncertainty due to field scattering from the surveyor's body 310
G.7.15 Measurement device 312
G.7.16 Fields out of measurement range 312
G.7.17 Noise 313
G.7.18 Integration time 313
G.7.19 Power chain 313
G.7.20 Positioning system 313
G.7.21 Matching between probe and the EUT 313
G.7.22 Drifts in output power of the EUT, probe, temperature, and humidity 313
G.7.23 Perturbation by the environment 313
G.8 Example influence quantities for RF field strength computations by ray tracing or full wave methods 314
G.8.1 General 314
G.8.2 System 314
G.8.3 Technique uncertainties 315
G.8.4 Environmental uncertainties 315
G.9 Influence quantities for SAR measurements 316
G.9.1 General 316
G.9.2 Post-processing 316
G.9.3 EUT holder 316
G.9.4 EUT positioning 317
G.9.5 Phantom shell uncertainty 318
G.9.6 SAR correction depending on target liquid permittivity and conductivity 318
G.9.7 Liquid permittivity and conductivity measurements 319
G.9.8 Liquid temperature 319
G.10 Influence quantities for SAR calculations 319
G.11 Spatial averaging 319
G.11.1 General 319
G.11.2 Small-scale fading variations 320
G.11.3 Error on the estimation of local average power density 321
G.11.4 Characterization of environment statistical properties 322
G.11.5 Characterization of different spatial averaging schemes 322
G.12 Influence of human body on measurements of the electric RF field strength 327
G.12.1 Simulations of the influence of human body on measurements based on the method of moments (surface equivalence principle) 327
G.12.2 Comparison with measurements 329
G.12.3 Conclusions 330
Annex H (informative) Guidance on comparing evaluated parameters with a limit value 331
H.1 Overview 331

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H.2 Information recommended to compare evaluated value against limit value 331
H.3 Performing a limit comparison at a given confidence level 331
H.4 Performing a limit comparison using a process-based assessment scheme 332
Bibliography 333

Figure 1 – Quick start guide to the evaluation process 40
Figure 2 – Example of iso-surface compliance boundary 43
Figure 3 – Example of cylindrical and half-pipe compliance boundaries 44
Figure 4 – Example of box shaped compliance boundary 45
Figure 5 – Example of truncated box shaped compliance boundary 45
Figure 6 – Example illustrating the linear scaling procedure 46
Figure 7 – Example of massive MIMO antenna and corresponding beams and envelope patterns 48
Figure 8 – Example of compliance boundary shape for BS antennas with beam steering 48
Figure 9 – Example of dish antenna compliance boundary 49
Figure 10 – Flowchart describing the product installation evaluation process 51
Figure 11 – Example of a CDF curve representing the normalized actual transmitted power or EIRP 53
Figure 12 – Flow chart for product installation compliance based on the actual maximum transmitted power or EIRP threshold(s) 55
Figure 13 – Simplified compliance assessment process using installation classes 56
Figure 14 – Example of DI within a square-shaped assessment domain boundary (ADB) with dimension L_{ADB} 60
Figure 15 – In-situ RF exposure evaluation or assessment process flow chart 65
Figure 16 – Source-environment plane concept 69
Figure 17 – Flow chart of the measurement methods 72
Figure 18 – Flow chart of the relevant computation methods 75
Figure 19 – Example of segments used for monitoring and control of BS using mMIMO or beam steering 77
Figure A.1 – Example source-environment plane regions near a base station antenna on a tower 83
Figure A.2 – Example source-environment plane regions near a roof-top antenna that has a narrow vertical (elevation plane) beamwidth (not to scale) 84
Figure A.3 – Geometry of an antenna with largest linear dimension L_{eff} and largest end dimension L_{end} 85
Figure A.4 – Maximum path difference for an antenna with largest linear dimension L 89
Figure B.1 – Cartesian, cylindrical and spherical coordinate systems relative to the BS antenna (view from the rear panel) 97
Figure B.2 – Typical RF exposure assessment case 99
Figure B.3 – Reflection due to the presence of a ground plane 100
Figure B.4 – Reflections due to the presence of internal walls of the housing and surrounding asphalt and soil configuring a base station installed underground 101
Figure B.5 – General representation of RF field strength or power density measurements 102
Figure B.6 – Practical examples of measurement equipment installation 103

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Figure B.7 – Spatial averaging schemes relative to walking or standing surface and in the vertical plane oriented to offer maximum area in the direction of the source being evaluated 105
Figure B.8 – Spatial averaging relative to spatial-peak field strength point height 107
Figure B.9 – Evaluation locations 119
Figure B.10 – Relationship of separation of remote radio source and evaluation area to separation of evaluation points 120
Figure B.11 – Outline of the surface scanning methodology 123
Figure B.12 – Block diagram of the antenna measurement system 124
Figure B.13 – Minimum radius constraint, where a denotes the minimum radius of a sphere, centred at the reference point, that encompasses the EUT 125
Figure B.14 – Maximum angular sampling spacing constraint 125
Figure B.15 – Outline of the volume/surface scanning methodology 128
Figure B.16 – Block diagram of typical near-field EUT measurement system 129
Figure B.17 – Examples of positioning of the EUT relative to the relevant phantom 136
Figure B.18 – Phantom liquid volume and measurement volume used for whole-body SAR measurements with the box-shaped phantoms 143
Figure B.19 – Reference frame employed for cylindrical formulas for RF field strength computation at a point P (left), and on a line perpendicular to boresight (right) 147
Figure B.20 – Views illustrating the three valid zones for field strength computation around an antenna 149
Figure B.21 – Enclosed cylinder around collinear array antennas, with and without electrical downtilt 150
Figure B.22 – Spherical formulas reference results 153
Figure B.23 – Cylindrical formulas reference results 153
Figure B.24 – Directions for which SAR estimation expressions are provided 154
Figure B.25 – Description of SAR estimation formulas physical parameters 155
Figure B.26 – Flow chart for the simplified assessment of RF compliance boundary in the line of sight of a parabolic dish antenna 162
Figure B.27 – Radiating cable geometry 163
Figure B.28 – Synthetic model and ray tracing algorithms geometry and parameters 167
Figure B.29 – Line 4 far-field positions for synthetic model and ray tracing validation example 169
Figure B.30 – Antenna parameters for synthetic model and ray tracing algorithms validation example 170
Figure B.31 – Generic 900 MHz BS antenna with nine dipole radiators 177
Figure B.32 – Line 1, 2 and 3 near-field positions for full wave and ray tracing validation 178
Figure B.33 – Generic 1 800 MHz BS antenna with five slot radiators 179
Figure B.34 – BS antenna placed in front of a multi-layered lossy cylinder 185
Figure B.35 – Time variation over 24 h of the exposure induced by NR, GSM and FM, each normalized to the mean value 189
Figure B.36– Generic structure of a base station transmitted RF signal frame 194
Figure B.37 – Example of setup for the direct power level measurement for BS equipped with direct access conducted output ports 201
Figure C.1 – Example of a laboratory test setup for validation of an actual power control feature intended for use with a 5G BS 210

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Figure C.2 – Example of a test setup for validation of an actual power control feature implemented in a 5G BS 213
Figure C.3 – Ground based in-situ validation setup 216
Figure C.4 – In-situ validation measurement setup near the general public compliance boundary in front of the 5G massive MIMO antenna (bore sight position) 217
Figure C.5 – Comparison between measured time-averaged EMF and power control feature (5G counter data) for the ground-based measurements 218
Figure C.6 – Measured exposure adaptation in time expressed as a percentage of ICNIRP limits [1], [2] for the measurements near the general public compliance boundary 218
Figure C.7 – Overview of the measurement site 220
Figure C.8 – Ground view of the validation site and measurement setup, located 60 m from the 5G BS, in the line of sight 221
Figure C.9 – Power transmitted by the massive MIMO antenna (top trace), channel power (ChP) measurements (middle trace) and transmitted resource blocks (RBs) (bottom trace) 221
Figure C.10 – Overview of the test platform 223
Figure C.11 – Example of synthetic model simulation of the test area 223
Figure C.12 – Examples of traffic load profiles 223
Figure C.13 – Example of testing in different segments in the test area 224
Figure C.14 – Results of the monitoring validation and baseline test in phase 1 225
Figure C.15 – Example of power density measurements and power density derived from counters 225
Figure C.16 – Measured power density and power density derived from counters 226
Figure C.17 – Comparisons of both counters and measurements 226
Figure D.1 – Measured ER as a function of distance for a BS (G = 5 dBi, f = 2 100 MHz) transmitting with an EIRP of 2 W (installation class E2) and 10 W (installation class E10) 227
Figure D.2 – Minimum installation height as a function of transmitting power corresponding to installation class E10 228
Figure D.3 – Compliance distance in the main lobe as a function of EIRP established in accordance with the far-field formula corresponding to installation class E100 229
Figure D.4 – Minimum installation height as a function of transmitting power corresponding to installation class E100 230
Figure D.5 – Averaged power density at ground level for various installation configurations of equipment with 100 W EIRP (installation class E100) 231
Figure D.6 – Compliance distance in the main lobe CD_m as a function of EIRP established in accordance with the far-field formula corresponding to installation class E+ 232
Figure D.7 – Minimum installation height h_m as a function of EIRP corresponding to installation class E+ 232
Figure D.8 – Power density distribution in watts per square metre in a vertical cut plane for an 8 × 8 antenna array at 28 GHz (grid step of 10 cm) 233
Figure D.9 – Power density distribution in watts per square metre in a vertical cut plane for an 8 × 8 antenna array at 39 GHz (grid step of 10 cm) 233
Figure E.1 – Spectral occupancy for GMSK 237
Figure E.2 – Spectral occupancy for CDMA 238
Figure E.3 – Channel allocation for a WCDMA signal 241
Figure E.4 – Example of Wi-Fi frames 244

IECNORM.COM : Click to view the full PDF of IEC 62232:2022

Figure E.5 – Channel occupation versus the integration time for IEEE 802.11b standard 245
Figure E.6 – Channel occupation versus nominal throughput rate for IEEE 802.11b/g standards 246
Figure E.7 – Wi-Fi spectrum trace snapshot 246
Figure E.8 – Frame structure of transmission signal for LTE-FDD downlink 250
Figure E.9 – Frame structure LTE-TDD type 2 (for 5 ms switch-point periodicity) 251
Figure E.10 – Frame structure of transmission signal for LTE-TDD 251
Figure E.11 – LTE-TDD PBCH measurement example 254
Figure E.12 – Example of VBW setting for LTE-FDD and LTE-TDD to avoid underestimation 255
Figure E.13 – Examples of received waves from LTE-FDD downlink signals using a spectrum analyser using zero span mode 256
Figure E.14 – LTE-TDD PBCH measurement example spectrum analyser using zero span mode 257
Figure E.15 – Example of VBW setting for NR to avoid underestimation 261
Figure E.16 – Examples of measurement accuracy results according to the ratio of VBW and RBW for NR SCS 30 kHz and 1 MHz RBW using various SA types (A to D) 261
Figure E.17 – Waterfall reconstruction plot of a 1 s long measurement trace of an NR signal with subcarrier spacing (SCS) 30 kHz (along one component of the electric field) 262
Figure E.18 – Example of NR signal frame measured on SA with SSB signal above PDSCH (data) 262
Figure E.19 – Example of NR signal frame measured on SA with SSB signal below or equal to PDSCH (data) 263
Figure E.20 – Time gating of SS burst signal 264
Figure E.21 – Representation of the channel bandwidth (CBW) 264
Figure E.22 – An example for one port CSI-RS beam design 267
Figure E.23 – Plan view representation of statistical conservative model 273
Figure E.24 – Binomial cumulative probability function for N = 24, PR = 0,125 281
Figure E.25 – Binomial cumulative probability function for N = 18, PR = 2/7 281
Figure E.26 – Binomial cumulative probability function for N = 100, PR = 0,125 285
Figure E.27 – Binomial cumulative probability function for N = 82, PR = 2/7 285
Figure F.1 – Limits for brief exposure (t < 360 s), seeTable F.1, divided by the corresponding time interval t and normalized with the value obtained for t up to 360 s 289
Figure F.2 – F_{PR_min} as a function of the pulse duration assuming a whole-body averaging time of 30 min 293
Figure F.3 – F_{PR_min} as a function of the pulse duration assuming an averaging time of 6 min 293
Figure G.1 – Examples of general assessment schemes 297
Figure G.2 – Target uncertainty scheme overview 298
Figure G.3 – Probability of the true value being above (respectively below) the evaluated value depending on the confidence level assuming a normal distribution 302
Figure G.4 – Plot of the calibration factors for E (not E^2) provided from an example calibration report for an electric field probe 305
Figure G.5 – Computational model used for the variational analysis of reflected RF fields from the front of a surveyor 311
Figure G.6 – EUT positioning equipment and different positioning errors 317

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Figure G.7 – Physical model of small-scale fading variations 320
Figure G.8 – Example of E-field strength variations in line of sight of an antenna operating at 2,2 GHz 320
Figure G.9 – Error at 95 % on average power estimation 321
Figure G.10 – 343 measurement points building a cube (centre) and different templates consisting of a different number of positions 323
Figure G.11 – Moving a template (Line 3) through the cube 324
Figure G.12 – Standard deviations for GSM 900, DCS 1800 and UMTS 326
Figure G.13 – Simulation arrangement 328
Figure G.14 – Body influence 328
Figure G.15 – Simulation arrangement 329

Table 1 – Quick start guide evaluation steps 41
Table 2 – Example of product installation classes where a simplified evaluation process is applicable (based on ICNIRP general public limits [1] and [2]) 57
Table 3 – Exposure metrics validity for evaluation points in each source region 71
Table 4 – Requirements for RF field strength and power density measurements 73
Table 5 – Whole-body SAR exclusions based on RF power levels 73
Table 6 – Requirements for SAR measurements 74
Table 7 – Applicability of computation methods for source-environment regions of Figure 16 75
Table 8 – Requirements for computation methods 75
Table A.1 – Definition of source regions 86
Table A.2 – Default source region boundaries 86
Table A.3 – Source region boundaries for antennas with maximum dimension less than 2,5 λ 87
Table A.4 – Source region boundaries for linear/planar antenna arrays with a maximum dimension greater than or equal to 2,5 λ 87
Table A.5 – Source region boundaries for equiphase radiation aperture (e.g. dish) antennas with maximum reflector dimension much greater than a wavelength 88
Table A.6 – Source region boundaries for radiating cables 88
Table A.7 – Far-field distance r measured in metres as a function of angle β 90
Table A.8 – Guidance on selecting between computation and measurement approaches 91
Table A.9 – Guidance on selecting between broadband and frequency selective measurement 92
Table A.10 – Guidance on selecting RF field strength measurement procedures 93
Table A.11 – Guidance on selecting computation methods 94
Table A.12 – Guidance on specific evaluation method ranking 95
Table B.1 – Dimension variables 97
Table B.2 – RF power variables 97
Table B.3 – Antenna variables 98
Table B.4 – Exposure metric variables 98
Table B.5 – Broadband measurement system minimum requirements 111
Table B.6 – Frequency selective measurement system minimum requirements 112

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Table B.7 – Example template for estimating the expanded uncertainty of an in-situ RF field strength measurement that used a frequency selective equipment 132
Table B.8 – Example template for estimating the expanded uncertainty of an in-situ RF field strength measurement that used a broadband equipment 133
Table B.9 – Example template for estimating the expanded uncertainty of a laboratory-based RF field strength or power density measurement using the surface scanning method 134
Table B.10 – Example template for estimating the expanded uncertainty of a laboratory-based RF field strength or power density measurement using the volume scanning method 135
Table B.11 – Numerical reference SAR values for reference dipoles and flat phantom – All values are normalized to a forward power of 1 W 140
Table B.12 – Phantom liquid volume and measurement volume used for whole-body SAR measurements [61], [77] 143
Table B.13 – Correction factor to compensate for a possible bias in the obtained general public whole-body SAR when assessed using the large box-shaped phantom for child exposure configurations [72] 143
Table B.14 – Measurement uncertainty evaluation template for EUT whole-body SAR test 144
Table B.15 – Measurement uncertainty evaluation template for whole-body SAR system validation 145
Table B.16 – Definition of boundaries for selecting the zone of computation 149
Table B.17 – Input parameters for cylindrical and spherical formulas validation 152
Table B.18 – Applicability of SAR estimation formulas 154
Table B.19 – Calculation of $A(f, d)$ 157
Table B.20 – Antenna parameters for SAR estimation formulas verification 159
Table B.21 – Verification data for SAR estimation formulas – front 159
Table B.22 – Verification data for SAR estimation formulas – axial and back 159
Table B.23 – Example template for estimating the expanded uncertainty of a synthetic model and ray tracing RF field strength computation 168
Table B.24 – Synthetic model and ray tracing power density reference results 171
Table B.25 – Example template for estimating the expanded uncertainty of a full wave RF field strength / power density computation 176
Table B.26 – Validation 1 full wave field reference results 178
Table B.27 – Validation 2 full wave field reference results 179
Table B.28 – Example template for estimating the expanded uncertainty of a full wave SAR computation 183
Table B.29 – Validation reference SAR results for computation method 185
Table B.30 – Relevant parameters for performing RF exposure modelling studies of a massive MIMO site or site cluster 195
Table B.31 – Measurement campaign parameters for performing RF exposure assessment of a massive MIMO site or site cluster 197
Table B.32 – Power combination factors applicable to the normalized actual transmitted power CDF in case of combination of multiple independent identical transmitters 199
Table B.33 – Power combination factors applicable to two independent transmitters with a ratio p in amplitude 200
Table C.1 – Relative difference between the measured averaged transmitted power and actual power counter value for systems that allow direct power level measurements 204

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Table C.2 – Correlation between the configured maximum power level and the level reported by actual power counters for BS that allow direct power level measurements 205
Table C.3 – Correlation between the configured time-averaged load levels and the actual power counter value for systems that allow direct power level measurements 205
Table C.4 – Relative difference between the configured maximum power, measured averaged transmitted power, and actual power counters for systems that do not support direct power level measurements 206
Table C.5 – Correlation between the configured power level and the level reported by power counters for BS that do not support direct power level measurements 207
Table C.6 – Correlation between time linearity of the configured maximum power level and the level reported by actual power counters for BS that do not support direct power level measurements 209
Table E.1 – Technology specific information 234
Table E.2 – Example of spectrum analyser settings for an integration per service 239
Table E.3 – Example constant power components for specific TDMA/FDMA technologies 240
Table E.4 – WCDMA decoder characteristics 242
Table E.5 – Signal configurations 242
Table E.6 – WCDMA generator setting for power linearity 243
Table E.7 – WCDMA generator setting for decoder calibration 243
Table E.8 – WCDMA generator setting for reflection coefficient measurement 244
Table E.9 – Uplink-downlink configurations 252
Table E.10 – Theoretical extrapolation factor, N_{RS}, based on frame structure given in 3GPP TS 36.104 [21] 253
Table E.11 – F_{BW} for each combination of BS channel bandwidth and SSB subcarrier spacing (SCS) for sub-6 GHz signals 259
Table E.12 – F_{BW} for each combination of BS channel bandwidth and SSB subcarrier spacing (SCS) for mm-wave signals 260
Table E.13 – List of variables in the case study 284
Table F.1 – Brief exposure limits for the general public integrated over intervals of between 0 min and 6 min as specified by ICNIRP-2020 [1] 289
Table F.2 – Minimum F_{PR}, F_{PR_min}, for which compliance with the time-averaged whole-body limits ICNIRP-2020 [1] inherently ensures compliance with the brief exposure limits specified by ICNIRP-2020 [1] 293
Table G.1 – Determining target uncertainty 298
Table G.2 – Monte Carlo simulation of 10 000 trials, both surveyor and auditor using best estimate 300
Table G.3 – Monte Carlo simulation of 10 000 trials, both surveyor and auditor using target uncertainty of 4 dB 300
Table G.4 – Monte Carlo simulation of 10 000 trials where surveyor uses upper 95 % CI and auditor uses lower 95 % CI 301
Table G.5 – Guidance on minimum separation distances for some dipole lengths such that the uncertainty does not exceed 5 % or 10 % in a measurement of E 309
Table G.6 – Guidance on minimum separation distances for some loop diameters such that the uncertainty does not exceed 5 % or 10 % in a measurement of H 309
Table G.7 – Example minimum separation conditions for selected dipole lengths for 10 % uncertainty in E 310
Table G.8 – Standard estimates of dB variation for the perturbations in front of a surveyor due to body reflected fields as described in Figure G.5 312

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Table G.9 – Standard uncertainty (u) estimates for E and H due to body reflections from the surveyor for common radio services derived from estimates provided in Table G.8 312
Table G.10 – Maximum sensitivity coefficients for liquid permittivity and conductivity over the frequency range 300 MHz to 6 GHz 319
Table G.11 – Uncertainty at 95 % for different fading models 322
Table G.12 – Correlation coefficients for GSM 900 and DCS 1800 325
Table G.13 – Variations of the standard deviations for the GSM 900, DCS 1800 and UMTS frequency bands 326
Table G.14 – Examples of total uncertainty calculation 327
Table G.15 – Maximum simulated error due to the influence of a human body on the measurement values of an omnidirectional probe 329
Table G.16 – Measured influence of a human body on omnidirectional probe measurements 329

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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DETERMINATION OF RF FIELD STRENGTH, POWER DENSITY AND SAR IN THE VICINITY OF BASE STATIONS FOR THE PURPOSE OF EVALUATING HUMAN EXPOSURE

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IEC 62232 has been prepared by IEC technical committee 106: Methods for the assessment of electric, magnetic and electromagnetic fields associated with human exposure. It is an International Standard.

This third edition cancels and replaces the second edition published in 2017. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) increased frequency range, from 110 MHz to 300 GHz (including consideration of ambient sources from 100 kHz to 300 GHz);
b) specification of assessment procedures based on the actual maximum approach including methods for the validation of monitoring counter and control features;
c) introduction of assessment methods relevant to 5G technologies and BS using beam-steering such as massive MIMO systems;
d) clarification of criteria for exposure from multiple sources;

e) restructuring of Annex B (Evaluation methods) for better readability;

f) update of the requirements and procedures for power density measurements in laboratory conditions;

g) update of simplified assessment formulas for dish antennas used in radio relays and microwave links;

h) compatibility with ICNIRP-2020 [1][1] exposure limits.

This document contains attached files that are cited in Figure B.30 and G.4.4.3. These files can be downloaded from https://www.iec.ch/tc106/supportingdocuments.

The text of this International Standard is based on the following documents:

Draft	Report on voting
106/576/FDIS	106/590/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at http://www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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[1] Numbers in square brackets refer to the Bibliography.

INTRODUCTION

This document addresses the evaluation of RF field strength, power density and specific absorption rate (SAR) levels in the vicinity of base stations (BS), also called products or equipment under test (EUT), intentionally radiating in the radio frequency (RF) range 110 MHz to 300 GHz in accordance with the scope, see Clause 1. It does not address the evaluation of current density.

RF exposure evaluation methods to be used for product compliance, product installation compliance and in-situ RF exposure assessments are specified in this document. Exposure limits are not specified in this document. The entity conducting RF exposure assessments refers to the set of exposure limits applicable where exposure takes place. Examples of applicable exposure limits considered in this document are provided in the Bibliography, for example ICNIRP-2020 [1], ICNIRP-1998 [2], IEEE Std C95.1™-2019 [3] and Safety Code 6 [4].

NOTE In this document, "ICNIRP" used without "-1998 or "-2020" applies to both [1] and [2].

This document is based on IEC 62232:2017 leveraging guidelines and lessons learned from the implementation guide IEC TR 62669:2019 [5]. In particular, it specifies how to implement the actual maximum approach.

Clause 2, Clause 3 and Clause 4 address normative references, terms and definitions, symbols, and abbreviated terms, respectively.

Clause 5 provides advice on how to use this document, including a quick-start guide.

Clause 6 describes the three main application areas of this document: RF exposure evaluation methods for product compliance, product installation compliance, and in-situ RF exposure assessments. It includes the key requirements for assessing RF exposure based on using the actual maximum approach. It also includes simplified criteria for putting BS into operation. Further details are provided in Annex C, Annex D and Annex E.

Clause 7 provides guidelines on how to select the evaluation method. Further details are provided in Annex A.

Clause 8 specifies the RF exposure evaluation methods to be used and refers to further details in Annex B, Annex C, Annex F and Annex H.

Clause 9 addresses the estimation of uncertainty and refers to Annex G and Annex H for further details.

Clause 10 describes reporting requirements for the evaluation or assessment.

Annexes and the bibliography are referenced extensively to provide useful clarifications or guidance.

Additional guidance can be found in IEC TR 62669:2019 [5], which includes a set of case studies providing practical examples of the application of this document.

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DETERMINATION OF RF FIELD STRENGTH, POWER DENSITY AND SAR IN THE VICINITY OF BASE STATIONS FOR THE PURPOSE OF EVALUATING HUMAN EXPOSURE

1 Scope

This document provides methods for the determination of RF field strength, power density and specific absorption rate (SAR) in the vicinity of base stations (BS) for the purpose of evaluating human exposure.

This document:

a) considers intentionally radiating BS which transmit on one or more antennas using one or more frequencies in the range 110 MHz to 300 GHz;

b) considers the impact of ambient sources on RF exposure at least in the 100 kHz to 300 GHz frequency range;

c) specifies the methods to be used for RF exposure evaluation for compliance assessment applications, namely:

   1) product compliance – determination of compliance boundary information for a BS product before it is placed on the market;

   2) product installation compliance – determination of the total RF exposure levels in accessible areas from a BS product and other relevant sources before the product is put into operation;

   3) in-situ RF exposure assessment – measurement of in-situ RF exposure levels in the vicinity of a BS installation after the product has been taken into operation;

d) specifies how to perform RF exposure assessment based on the actual maximum approach;

e) describes several RF field strength, power density, and SAR measurement and computation methodologies with guidance on their applicability to address both the in-situ evaluation of installed BS and laboratory-based evaluations;

f) describes how surveyors establish their specific evaluation procedures appropriate for their evaluation purpose;

g) provides guidance on how to report, interpret and compare results from different evaluation methodologies and, where the evaluation purpose requires it, determine a justified decision against a limit value;

h) provides methods for the RF exposure assessment of BS using time-varying beam-steering technologies such as new radio (NR) BS using massive multiple input multiple output (MIMO).

NOTE 1 Practical implementation case studies are provided as examples in the companion Technical Report IEC TR 62669:2019 [5].

NOTE 2 Although the current BS product types have been specified to operate up to 200 GHz (see, for example, [6] and [7]), the upper frequency of 300 GHz is consistent with applicable exposure limits.

NOTE 3 The lower frequency considered for ambient sources, 100 kHz, is derived from ICNIRP-1998 [2] and ICNIRP-2020 [1]. However, some applicable exposure guidelines require ambient fields to be evaluated as low as 3 kHz, e.g. Safety Code 6 [4] and IEEE Std C95.1-2019 [3].

NOTE 4 Specification of appropriate RF exposure mitigation measures such as signage, access control, and training are beyond the scope of this document. It is possible to refer to the applicable regulations or recommended practices on these topics.

NOTE 5 While this document is based on the current international consensus about the best engineering practice for assessing the compliance of RF exposure with the applicable exposure limits, it is possible that national regulatory agencies specify different requirements. The entity conducting an RF exposure assessment needs to be aware of the applicable regulations.

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2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC/IEEE 62209-1528, *Human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Human models, instrumentation, and procedures: Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices (Frequency range of 4 MHz to 10 GHz)*

IEC 62209-3, *Measurement procedure for the assessment of specific absorption rate of human exposure to radio frequency fields from hand-held and body-mounted wireless communication devices – Part 3: Vector measurement-based systems (Frequency range of 600 MHz to 6 GHz)*

IEC 62311, *Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz – 300 GHz)*

IEC 62479, *Assessment of the compliance of low power electronic and electrical apparatus with the basic restrictions related to human exposure to electromagnetic fields (10 MHz – 300 GHz)*

IEC/IEEE 62704-1, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 1: General requirements for using the finite difference time-domain (FDTD) method for SAR calculations*

IEC/IEEE 62704-2, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 2: Specific requirements for finite difference time domain (FDTD) modelling of exposure from vehicle mounted antennas*

IEC/IEEE 62704-3, *Determining the peak spatial-average specific absorption rate (SAR) in the human body from wireless communications devices, 30 MHz to 6 GHz – Part 3: Specific requirements for using the finite difference time domain (FDTD) method for SAR calculations of mobile phones*

IEC/IEEE 62704-4, *Recommended practise for determining the Peak Spatial Average Specific Absorption Rate (SAR) in the human body from wireless communications devices, 30 MHz – 6 GHz: General requirements for using the Finite-Element Method (FEM) for SAR calculations and specific requirements for modelling vehicle-mounted antennas and personal wireless devices*

IEC/IEEE 63195-1, *Measurement procedure for the assessment of power density of human exposure to radio frequency fields from wireless devices operating in close proximity to the head and body – Frequency range of 6 GHz to 300 GHz*

IEC/IEEE 63195-2, *Determining the power density of the electromagnetic field associated with human exposure to wireless devices operating in close proximity to the head and body using computational techniques, 6 GHz to 300 GHz*

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3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
absorbed energy density
U_{ab}
temporal integration of the absorbed power density, S, between time t_1 and t_2

Note 1 to entry: Given by the following equation from ICNIRP-2020 [1]:

$$U_{ab} = \int_{t_1}^{t_2} S_{ab}(t)\,dt$$

where

S_{ab} is the absorbed power density;

t_1 is the start time of the assessment;

t_2 is the stop time of the assessment.

3.2
absorbed power
P_A
RF power dissipated in a volume V

Note 1 to entry: Given by

$$P_A = \int_V \sigma(x,y,z)\left[E(x,y,z)\right]^2 dV$$

where

$E(x,y,z)$ is the RMS value of the electric field strength in the absorbing material at the point (x,y,z) in volt per metre;

$\sigma(x,y,z)$ is the electric conductivity of the absorbing material at the point (x,y,z) in siemens per metre.

3.3
absorbed power density
S_{ab}
spatial average over an area A of the power dissipated per unit of body surface

Note 1 to entry: Given by the following equation derived from ICNIRP-2020 [1]

$$S_{ab} = \frac{1}{A} \cdot \iint_A \mathrm{Re}\left[\vec{S}\right] \cdot d\vec{s}$$

where

$\mathrm{Re}\left[\vec{S}\right]$ is the real part of the complex Poynting vector $\vec{s}$;

$d\vec{s}$ is the integral variable vector with its direction normal to A;

A is the averaging area.

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3.4
actual
<transmitted power or EIRP or exposure> time-average of the transmitted power or EIRP or exposure from the equipment under test (EUT) in operation using the actual averaging time

3.5
actual averaging time
T_{avg_act}
time duration used for the averaging of the transmitted power or EIRP or exposure when implementing the actual maximum approach

3.6
actual maximum
<transmitted power or EIRP or exposure> maximum of the actual transmitted power or EIRP or exposure from the EUT during a given period (e.g. week or month)

3.7
actual maximum approach
evaluation of RF exposure taking into account the actual maximum thereof

3.8
actual maximum threshold
<actual transmitted power or EIRP> upper limiting value during base station (BS) operation of the actual transmitted power or EIRP configured by the EUT, for example using transmitted power or EIRP control features and tools implemented in the EUT

3.9
ambient field
background electromagnetic field in the frequency range from at least 100 kHz to 300 GHz other than the emissions from the EUT in the frequency range 110 MHz to 300 GHz

Note 1 to entry: Some applicable exposure guidelines require ambient fields to be considered as low as 3 kHz, e.g. Safety Code 6 [4] and IEEE Std C95.1-2019 [3].

3.10
ambient source
transmitter generating ambient fields

3.11
antenna factor
ratio of the electromagnetic field strength incident upon an antenna to the voltage (U) that is produced across a specified impedance (e.g. 50 Ω) terminating the line connection of the antenna

3.12
assessment
undertaking of an evaluation of RF exposure from an EUT in order to arrive at a judgement about comparison with the applicable exposure limits

3.13
assessment configuration
set of parameters which together represent the base station (BS) configuration to be assessed in accordance with the evaluation purpose, e.g. for conformity assessment

3.14
assessment domain boundary
ADB
surface surrounding the EUT outside of which the total exposure ratio (TER) is lower than 0,05

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Note 1 to entry: It is possible that applicable regulations consider exposure ratio (ER) lower than 0,05 to be relevant (e.g. 0,01 of the measured TER).

3.15
assessment scheme
synopsis of the assessment process

EXAMPLE Measurements compared to limit value considering uncertainty.

3.16
auditor
person(s) having the appropriate level of expertise and responsible for planning, executing and reporting on the evaluation of RF field strength, power density or SAR levels and responsible for the verification of RF exposure compliance

Note 1 to entry: The auditor can be a member of the regulatory agency or a third-party RF safety consultant. As an example, a company could audit the compliance of their own facility, or a second RF safety consultant could audit the results of an initial survey.

3.17
average transmitted power
time-averaged transmitted power
P_{avg}
rate of transmitted energy transfer expressed in watts

Note 1 to entry: Given by

$$P_{avg} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} P(t) \mathrm{d}t$$

where

t_1 is the start time of the observation in seconds;

t_2 is the stop time of the observation in seconds;

$P(t)$ is the instantaneous transmitted power in watts.

3.18
averaging time
T_{avg}
time duration specified in the applicable exposure limit guidelines over which exposure is averaged

Note 1 to entry: Depending on the applicable exposure limits, T_{avg} can take different values for localized RF exposure (T_{avg_local}) or whole-body exposure (T_{avg_wb}); see, for example, [1].

3.19
base station
product
equipment under test
BS
EUT
equipment, permanently or temporarily installed, including the radio transmitter and associated antenna(s) as used in wireless telecommunications networks

EXAMPLE Base stations for mobile communications, radio-relays, wireless local area network access points, base stations for cordless telephony, etc. that are not normally used in close proximity (i.e. within 20 cm) to the human body.

Note 1 to entry: Examples of wireless telecommunications networks include those used in mobile telecommunication systems in accordance with ITU-R M.1224-1 [8], wireless local area networks, public safety networks and fixed wireless systems (including radio-relay systems, point-to-point communication and point-to-multipoint communication in accordance with ITU-R F.592-4 [9] and ITU-R F.1339-1 [10]).

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Note 2 to entry: In the context of this document, radar transmitters, TV and radio broadcast equipment are not considered to be base station equipment.

3.20
basic restriction
exposure limit value specified in terms of an internal electromagnetic quantity in the body, such as specific absorption rate (SAR), arising from exposure to incident external electromagnetic fields

Note 1 to entry: More detailed rationale and definitions are provided in the applicable exposure guidelines; see, for example ICNIRP-2020 [1], ICNIRP-1998 [2], IEEE Std C95.1-2019 [3] and Safety Code 6 [4]. It is possible that alternative terms for basic restriction are used, such as dosimetric reference limit (DRL) specified in IEEE Std C95.1-2019 [3].

3.21
broadcast control channel
BCCH
logical broadcast channel used by the base station in a GSM network to send information about the identity of the network

3.22
broadcast EIRP envelope
EIRP envelope considering the configured broadcast beam patterns and the configured maximum transmitted power

3.23
broadcast radiation pattern envelope
configured envelope radiation pattern considering the broadcast beam patterns

3.24
broadcast signal
stable reference signal used in a base station (BS) to transmit synchronization signals and not subject to time variation due to user equipment (UE) traffic, comprising physical broadcast channel (PBCH) for 5G or reference signal (RS) for 4G LTE

3.25
carrier
in a modulated signal, the spectral component of a modulated signal having the frequency of the periodical carrier prior to modulation

Note 1 to entry: Carrier is often used as an equivalent to channel.

[SOURCE: IEC 60050-702:1992, 702-06-06 [11]]

3.26
channel
section of RF spectrum with a given frequency and bandwidth used for the transmission of a signal

Note 1 to entry: Carrier is often used as an equivalent to channel.

Note 2 to entry: Subcarrier or specific channel, e.g. physical broadcast channel (PBCH), can be used to represent a section of a channel.

3.27
collinear array antenna
antenna consisting of a linear array of radiating elements, usually dipoles, with their axes lying in a straight line

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3.28
compliance boundary
CB
surface of arbitrary shape defining a volume outside of which the applicable exposure limit is not exceeded

3.29
compliance distance
CD
distance from the EUT antenna to the compliance boundary for a stated direction and set of transmission conditions

Note 1 to entry: In the absence of a stated direction, the compliance distance is the maximum distance from the EUT antenna to the compliance boundary.

3.30
configured envelope radiation pattern
non-physical radiation pattern obtained by taking, for each azimuth and elevation direction, the maximum performance among the set of the radiation patterns of the base station antenna configured during operation

3.31
configured maximum
<transmitted power or EIRP> RMS maximum of the <transmitted power or EIRP> value as configured in the network manager of the base station

Note 1 to entry: This does not include the technology duty-cycle factor.

3.32
control boundary
set of locations which together specify where human access to a compliance boundary is restricted by either warnings or physical controls

3.33
cumulative distribution function
CDF
<of a real-value random variable X evaluated at x> probability that X takes a value less than or equal to x

3.34
directivity
D
<of an antenna, in a given direction> ratio of the radiation intensity produced by an antenna in a given direction to the value of the radiation intensities averaged across all directions in space

Note 1 to entry: If no direction is specified, the direction of maximum radiation intensity from the given antenna is implied.

Note 2 to entry: The directivity is independent of antenna losses and equal to the absolute gain in the same direction if the antenna has no internal losses.

Note 3 to entry: The ratio can also be expressed in decibels: dBi for decibels relative to an isotropic radiator, or dBd for decibels relative to a half-wave dipole having a gain of 2,15 dBi.

3.35
dish antenna
parabolic antenna usually used for radio-relays or point-to-point communications

Note 1 to entry: See more in ITU-R F.592-4 [9] and ITU-R F.1339-1 [10].

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3.36
domain of investigation
DI
volume within the assessment domain boundary (ADB) where there is access and where an RF exposure evaluation or assessment is performed

Note 1 to entry: Access in this context refers to any part of the body being within the ADB under normal conditions.

3.37
dynamic range
<of an exposure metric> difference, over a given period of time, between maximum and minimum values of an exposure metric, expressed in decibels

Note 1 to entry: In some cases, the dynamic range can be expressed as an interval.

3.38
electric field strength
E-field strength
E
vector field quantity E which exerts on any charged particle at rest a force F equal to the product of E and the electric charge Q of the particle:

$F = Q \cdot E$

[SOURCE: IEC 60050-121:1998, 121-11-18 [12]]

3.39
equivalent isotropic radiated power
EIRP
product of the radio frequency input power into an antenna and the absolute gain of the antenna in a given direction relative to an isotropic radiator

[SOURCE: IEC 60050-712:2021, 712-02-51 [13], modified – In the term, "isotropically" has been replaced by "isotropic"; in the definition, "power supplied by a radio transmitter to" has been replaced by "radio frequency input power into" and "relative to an isotropic radiator" has been added.]

3.40
evaluation
<of an exposure metric> process of determining a value of an exposure metric

3.41
evaluation configuration
set of parameter values which together represent the base station configuration used in the evaluation

3.42
evaluation location
specific physical location at which a single parameter value or multiple field parameter values have been measured or computed

Note 1 to entry: In the case of spatial averaging, this is the reference location specified in the spatial averaging scheme.

3.43
evaluation purpose
reason for performing the RF exposure evaluation, such as product compliance, product installation compliance, or in-situ evaluation

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3.44
exposure limit
exposure limit value
maximum value of an electromagnetic quantity a person can be exposed to from time-varying electric, magnetic, and electromagnetic fields, that is specified by the applicable RF exposure guidelines in terms of basic restrictions and reference levels including, when applicable, frequency dependency, spatial averaging and time averaging

Note 1 to entry: Exposure limits are not specified in this document. The entity conducting the RF exposure assessment needs to be aware of the applicable exposure guidelines. Examples of applicable exposure limits considered in this document are provided in the bibliography, for example ICNIRP-2020 [1], ICNIRP-1998 [2], IEEE Std C95.1-2019 [3] and Safety Code 6 [4].

3.45
exposure metric
electromagnetic quantity used for specifying exposure limit values

Note 1 to entry: More detailed rationale and definition is provided in IEEE Std C95.3™-2021 [14].

3.46
exposure ratio
ER
ratio of the exposure metric and the applicable exposure limit, both expressed in terms of power

EXAMPLE $\mathrm{ER} = \frac{S}{S_{\mathrm{lim}}}$, $\mathrm{ER} = \max\left[\left(\frac{E}{E_{\mathrm{lim}}}\right)^2, \left(\frac{H}{H_{\mathrm{lim}}}\right)^2\right]$, where S_{lim}, E_{lim} and H_{lim} are the applicable limits.

Note 1 to entry: The exposure ratio can also be expressed as a percentage of the applicable exposure limit, i.e. ER % = ER (dimensionless) × 100 %.

3.47
frequency response
<of a probe> curve representing the variations, with respect to frequency, of the indicated level of the exposure metric of a probe

3.48
full buffer
base station traffic model with one or multiple user equipments (UEs) in a cell characterized by a constant number of connected UEs and the buffers of the UE related data flows continuously having an unlimited amount of data to transmit

Note 1 to entry: Derived from [15].

3.49
full wave
<method> computational method to solve the Maxwell's equations for electromagnetic waves numerically without any initial physical approximations being made

3.50
gain
G
ratio of the radiation intensity produced by a given antenna in a given direction to the radiation intensity that would be obtained if the power accepted by the antenna were radiated equally in all directions

Note 1 to entry: If no direction is specified, the direction of maximum radiation intensity from the given antenna is implied.

Note 2 to entry: When the absolute gain is expressed in decibels, the notation dBi is recommended by the International Telecommunication Union as a unit symbol.

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3.51
general public
GP
all persons not classified as worker

3.52
in-situ RF exposure evaluation
determination of in-situ RF exposure levels in the vicinity of a base station installation during operation

3.53
incident energy density
U_{inc}
temporal integration of the power density, S, between time t_1 and t_2

Note 1 to entry: Given by the following equation derived from ICNIRP-2020 [1]:

$$U_{\text{inc}} = \int_{t_1}^{t_2} S(t)\,\mathrm{d}t$$

where

S is the power density;

t_1 is the start time of the assessment;

t_2 is the stop time of the assessment.

Note 2 to entry: In the context of this document, "power density" S is used in this definition instead of "incident power density" introduced in ICNIRP-2020 [1].

3.54
intended use
reasonably foreseeable use of a base station for the purpose intended, over its full range of applicable functions, in accordance with the instructions provided by the manufacturer, including installation and operation instructions

3.55
licensed assisted access
LAA
variant of LTE used with unlicensed frequency band

3.56
linearity
<of a curve> deviation from a straight line of a curve representing an output quantity as a function of an input quantity

3.57
localized RF exposure
value of RF exposure averaged over a small area or volume or mass as specified by applicable RF exposure guidelines

3.58
local SAR
SAR averaged within a local region based on a specific averaging mass

3.59
lower detection limit
minimum quantifiable response of an item of measuring equipment

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3.60
magnetic field strength
H-field strength
H
vector quantity obtained at a given point by subtracting the magnetization M from the magnetic flux density B divided by the permeability of free space μ_0:

$$H = \frac{B}{\mu_0} - M$$

Note 1 to entry: In a vacuum, the magnetic field strength is at all points equal to the magnetic flux density divided by the permeability of free space:

$$H = \frac{B}{\mu_0}$$

Note 2 to entry: The rotation of the magnetic field strength is the total of the conduction and displacement current density J_t:

$$\text{rot}\, H = J_t$$

Note 3 to entry: The magnetic flux density B is sometimes called "magnetic field", risking confusion with the magnetic field strength H.

[SOURCE: IEC 60050-121:1998, 121-11-56 [12]]

3.61
massive MIMO
massive multiple-input, multiple-output
mMIMO
multi-antenna technique, characterized by a large number of antennas (typically above eight) to allow beamforming and beam-steering in addition to MIMO techniques improving communication performance, capacity and coverage

Note 1 to entry: More details on massive MIMO techniques can be found in [16].

3.62
massive MIMO antenna
antenna used with a BS implementing massive MIMO techniques

Note 1 to entry: The term "massive MIMO antenna" is often used in this document with the same meaning as time-varying beam-steering antenna.

3.63
maximum transmitted power
P_{TXM}
maximum total power transmitted by a base station measured during the transmitter ON period

Note 1 to entry: This applies either to the rated or configured power.

3.64
measurement drift
power drift
gradual deviation over time from a reproducible reading of the measured value

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3.65
measurement system
equipment used for measuring exposure metrics which can include probes, antennas, meters, amplifiers, chambers, stands, and associated components

3.66
multiple-input, multiple-output
MIMO
technique used to increase the communication throughput by using transmission of two or more different data streams on two or more different antennas, using the same resources in both frequency and time, separated only by the use of different reference signals, and to be received by two or more antennas

3.67
network management system
NMS
system providing a package of end-user functions with the responsibility for the management of a network, mainly as supported by the element managers but also involving direct access to the network elements in a mobile network

3.68
network performance tool
tool for taking active measurements of the maximum achievable bandwidth on an IP network

3.69
new radio
NR
5G mobile network technology as specified by the 3rd Generation Partnership Project (3GPP)

Note 1 to entry: See, for example, 3GPP 38.104 [17] for the specification of NR base stations.

3.70
peak antenna gain
G_p
maximum value of the gain considering all radiating directions

3.71
peak spatial-average SAR
psSAR
maximum SAR averaged within a local region based on a specific averaging mass

Note 1 to entry: A specific averaging mass can be, for example, any 1 g or 10 g of tissue in the shape of a cube.

Note 2 to entry: In this document, the terms psSAR (over 1 g or 10 g) and the terms 1 g SAR and 10 g SAR are used interchangeably.

3.72
physical broadcast channel
PBCH
transmission channel that is used to transfer information to all user equipments (UEs) that are operating in a radio coverage area

Note 1 to entry: See 3GPP TS 36.211 [18] for LTE and 3GPP TS 38.211 [19] for NR.

3.73
physical downlink control channel
PDCCH
channel that carries scheduling assignments and other control information

Note 1 to entry: See 3GPP TS 36.211 [18] for LTE and 3GPP TS 38.211 [19] for NR.

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3.74
physical downlink shared channel
PDSCH
downlink data channel for users

Note 1 to entry: See 3GPP TS 36.211 [18] for LTE and 3GPP TS 38.211 [19] for NR.

Note 2 to entry: A physical resource block thus consists of 7 × 12 resource elements, corresponding to one slot in the time domain and 180 kHz in the frequency domain.

Note 3 to entry: In NR technology, different number of symbols and subcarriers are possible. (from 3GPP TS 38.211 [19]).

3.75
plane wave equivalent power density
power density equal in magnitude to the power density of a plane wave

3.76
point of investigation
PoI
location of the maximum RF exposure when performing a slow scan over a measurement area at a height of 1,5 m above the walking or standing surface

3.77
power combination factor
multiplication factor that is applied to the power reduction factor in cases where a combination of multiple independent signals exists

3.78
power density
<of an electromagnetic wave> power passing through a surface normal to the direction of propagation of energy of an electromagnetic wave divided by the area of the surface

3.79
power reduction factor
F_{PR}
factor applied to the product of the configured maximum transmitted power or EIRP and the technology duty-cycle factor in order to obtain the actual maximum transmitted power or EIRP, or the actual maximum power or EIRP threshold, when a control feature is implemented

Note 1 to entry: The power reduction factor can be obtained from statistical analysis (cumulative distribution function) of the actual transmitted power or EIRP relative to the configured maximum.

Note 2 to entry: When applied to EIRP, the power reduction factor includes variations in both the transmitted power and the antenna gain.

3.80
probe isotropy
degree to which the response of an electric field or magnetic field probe is independent of the polarization and direction of propagation of the incident wave

3.81
product compliance
determination of compliance boundary information for a BS product before it is placed on the market

3.82
product envelope radiation pattern
envelope radiation pattern considering all beam patterns configurable on a BS product

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3.83
product installation compliance
determination that the total RF exposure in accessible areas from a BS product and other relevant sources is in compliance with applicable limits before the product is put into operation, for its first use or after an upgrade impacting its emission parameters

Note 1 to entry: Emission parameters include transmitted power or frequency, gain, tilt and azimuth.

3.84
radiation intensity
RF power radiated per solid angle

3.85
rated maximum
<of the transmitted power or EIRP> RMS maximum of the transmitted power or EIRP value as declared by the manufacturer when placing the product on the market

3.86
reference level
exposure limit value specified in terms of an incident electromagnetic quantity such as externally applied electric field strength, magnetic field strength or power density, that is easier to measure or calculate than the underlying basic restrictions, and that when respected, results in compliance with these basic restrictions

Note 1 to entry: More detailed rationale and definitions are provided in the applicable exposure guidelines; see, for example ICNIRP-2020 [1], ICNIRP-1998 [2], IEEE Std C95.1-2019 [3] and Safety Code 6 [4].

3.87
relevant source
RF source with an ER equal to or greater than 0,05 to be considered when performing an RF exposure assessment

Note 1 to entry: It is possible that applicable regulations consider ER criteria lower than 0,05 to be relevant (e.g. 0,01 of the measured TER).

Note 2 to entry: Not to be confused with source of interest.

3.88
resource block
RB
<LTE system> series of N = 6 (in the case of extended cyclic prefix) or N = 7 (in the case of a normal cyclic prefix) consecutive OFDM symbols in the time domain and N = 12 consecutive subcarriers in the frequency domain in an LTE system

Note 1 to entry: Derived from 3GPP TS 36.211 [18] (LTE).

3.89
resource block
RB
<NR system> series of N = 12 consecutive subcarriers in the frequency domain in an NR system

Note 1 to entry: Derived from 3GPP TS 38.211 [19] (NR).

3.90
resource element
RE
OFDM symbol transmitted in the resource grid of an LTE or NR system

Note 1 to entry: Derived from 3GPP TS 36.211 [18] and 3GPP TS 38.211 [19].

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3.91
RF field strength
electric field strength and/or magnetic field strength from an RF source

3.92
segment
<of a BS sector or a BS cell> solid angle in front of a BS sector or a BS cell described by an azimuth aperture range (delimited by an initial angle φ_i and a final angle φ_{i+1}) and elevation aperture range (delimited by an initial angle θ_j and a final angle θ_{j+1})

3.93
source
RF source
electronic equipment intentionally transmitting an RF signal

Note 1 to entry: Electronic equipment supporting wireless power transfer can be considered an RF source.

3.94
source-environment plane
method to identify the evaluation regions to be considered in the evaluation point selection based on environmental complexity and distance from the source

3.95
source of interest
RF source with an ER equal to or greater than −40 dB (or 0,000 1) to be considered when performing in-situ measurements for presenting RF exposure measurement results even if they are well below the exposure limits

Note 1 to entry: Not to be confused with relevant source.

Note 2 to entry: The ER threshold can be adjusted depending on the applicable regulation.

3.96
source region
spatial volume surrounding an antenna, divided into three regions in accordance with the impact the field characteristics have on the evaluation of the RF field strength, power density or SAR

Note 1 to entry There are two source regions near the antenna, called source region I and source region II, and one at a larger distance, called source region III. These source regions can be referred to as the reactive near-field, the radiative near-field, and the far-field, respectively.

3.97
spatial averaging scheme
method used to perform spatial averaging of RF exposure

3.98
spatial-peak
<electric field, magnetic field, SAR or power density> non-spatially averaged peak value of the electric field, magnetic field, SAR or power density

3.99
specific absorption rate
SAR
time derivative of the incremental electromagnetic energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of given mass density (ρ)

$$\mathrm{SAR} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\mathrm{d}m}\right) = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}W}{\rho \mathrm{d}V}\right)$$

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Note 1 to entry: SAR can be obtained using the following equation:

$$\mathrm{SAR} = \frac{\sigma \cdot E^2}{\rho}$$

where

SAR is the specific absorption rate in watts per kilogram (W kg^{-1});
E is the RMS value of the electric field strength in the tissue in volt per metre;
σ is the electric conductivity of the tissue in siemens per metre;
ρ is the density of the tissue in kilograms per cubic metre.

Note 2 to entry: The time derivative of energy absorbed is equivalent to absorbed power as specified in 3.1.

3.100
specific energy absorption
SEA
incremental electromagnetic energy (dW) absorbed by (dissipated in) an incremental mass (dm) contained in a volume element (dV) of given mass density (ρ)

$$\mathrm{SEA} = \frac{\mathrm{d}W}{\mathrm{d}m} = \frac{\mathrm{d}W}{\rho \mathrm{d}V}$$

3.101
sub-carrier
<OFDM> one of a large number of closely spaced or overlapping orthogonal narrow-bandwidth data signals within an OFDM channel

Note 1 to entry: Derived from 3GPP TS 36.211 [18] and 3GPP TS 38.211 [19].

3.102
sub-carrier spacing
<OFDM> frequency separation between OFDM sub-carriers

Note 1 to entry: Derived from 3GPP TS 36.211 [18] and 3GPP TS 38.211 [19].

3.103
surveyor
person or persons having the appropriate level of expertise and responsible for planning, executing and reporting on the evaluation of RF field strength, power density or SAR levels

3.104
technology duty-cycle factor
F_{TDC}
ratio of the time that a transmitter transmits over a specified period

Note 1 to entry: For frequency division duplex (FDD) systems, the technology duty-cycle factor is 1.

3.105
time-averaged
<transmitted power or EIRP or exposure> average value of the transmitted power or EIRP or exposure over a relevant time period

3.106
traffic EIRP envelope
EIRP envelope considering the configured traffic beam patterns and the configured maximum transmitted power

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3.107
traffic radiation pattern envelope
configured envelope radiation pattern considering the traffic beam patterns

3.108
traffic signal
downlink signal used by a BS to transmit user's traffic data and subject to time variation due to traffic and spatial variation in case of beamforming

Note 1 to entry: In mobile radio technologies using active antenna systems (AAS), broadcast signals and traffic signals can be transmitted on different beams, having different radiation patterns. Broadcast signals can be transmitted on a single beam, whose radiation pattern does not change in time, or on a finite set of beams, whose patterns do not change in time, swept periodically. Traffic signals are transmitted on a complex combination of beams depending on the antenna's beamforming implementation, such as grid of beam (GoB) or eigen-beamforming (EBB).

3.109
transmitted power
P_{TX}
instantaneous total power transmitted by a base station under test during the transmitter ON period

3.110
upper detection limit
maximum quantifiable response of a measuring equipment

3.111
user equipment
UE
device used directly by an end-user to communicate in a mobile network

3.112
whole-body RF exposure
RF exposure averaged over the whole body, at a reference location identified in the spatial averaging scheme

3.113
worker
adult who is generally exposed to RF fields under known conditions and is trained to be aware of potential risks related to RF exposure and to take appropriate precautions

Note 1 to entry: It is possible that applicable regulations consider a different definition for worker and use the term "RF worker".

Note 2 to entry: It is possible that applicable regulations consider occupational exposure limits for workers.

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4 Symbols and abbreviated terms

4.1 Physical quantities

The internationally accepted SI units are used throughout this document.

Symbol	Quantity	Unit	Dimensions
α	Attenuation coefficient	reciprocal metre	m^{-1}
B	Magnetic flux density	tesla	T, V s m^{-2}
c_h	Specific heat capacity	joule per kilogram per kelvin	J kg^{-1} K^{-1}
E	Electric field strength	volt per metre	V m^{-1}
f	Frequency	hertz	s^{-1}
H	Magnetic field strength	ampere per metre	A m^{-1}
J	Current density	ampere per square metre	A m^{-2}
T	Temperature	kelvin	K
ε	Permittivity	farad per metre	F m^{-1}
λ	Wavelength	metre	m
μ	Permeability	henry per metre	H m^{-1}
P	Power	watts	W
S	Power density	watts per square metre	W m^{-2}
Ω	Resistance	ohm	V A^{-1}
ρ	Mass density	kilogram per cubic metre	kg m^{-3}
σ	Electric conductivity	siemens per metre	S m^{-1}

NOTE 1 In this document, temperature is quantified in degrees Celsius, as specified by: T (°C) = T (K) − 273,16.

NOTE 2 Annex A and Clause B.2 specify additional symbols and variables used in this document.

4.2 Constants

Symbol	Physical constant	Magnitude
c	Speed of light in vacuum	2,997 9 × 10^8 m s^{-1}
η_0	Impedance of free space	376,730 3 Ω (approximately 120π Ω)
ε_0	Permittivity of free space	8,854 188 × 10^{-12} F m^{-1}
μ_0	Permeability of free space	4π × 10^{-7} H m^{-1}

4.3 Abbreviated terms

Abbreviation	Term
2G/3G/4G/5G	generations of mobile radio technology
4K HD	ultra-high definition
AAS	active antenna system
ADB	assessment domain boundary
AMPS	advanced mobile phone system
BCCH	broadcast control channel
BS	base station
CB	compliance boundary

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Abbreviation	Term
CD	compliance distance
CDD	cyclic delay diversity
CDF	cumulative distribution function
CDMA	code division multiple access
CF	correction factor
ChP	channel power
Co-pol	co-polarization
CI	confidence interval
CP	cyclic prefix
CPICH	common pilot channel
CRS	cell-specific reference signal
CSI-RS	channel state information – reference signal
CTRL	control
CW	continuous wave
DAB	digital audio broadcasting
DCI	downlink control information
DECT	digital enhanced cordless telecommunications
DI	domain of investigation
DL	downlink
DMRS	demodulation reference signal
DPCH	dedicated physical channel
DRL	dosimetric reference limit
DSS	dynamic spectrum sharing
E-field	electric field
EBB	eigen-based beamforming or eigen-beamforming or eigen-value based beamforming
eMBB	enhanced mobile broadband
EIRP	equivalent isotropic radiated power or equivalent isotropically radiated power
EM	electromagnetic
EMF	electromagnetic fields (includes electric, magnetic and electromagnetic fields)
ER	exposure ratio
EUT	equipment under test
FCC	federal communications commission
FDD	frequency division duplex
FDMA	frequency division multiple access
FDTD	finite difference time domain
FEM	finite element method
FIT	finite integration technique
FM	frequency modulation
GoB	grid of beam
GP	general public or general population

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Abbreviation	Term
GSCN	global synchronization channel number
GSM	global system for mobile communications (originally *Groupe Spécial Mobile*)
H-field	magnetic field
HD	high definition
HPBW	half-power beamwidth
ICNIRP	International Commission on Non-Ionizing Radiation Protection
IP	Internet Protocol
ISM	industrial, scientific and medical
LAA	licensed assisted access
LoS	line of sight
LTE	long term evolution
MAC	media access control
MIMO	multiple-input, multiple output
mMIMO	massive MIMO
MoM	method of moments
NLoS	non line of sight
NM	network manager
NMT	nordic mobile telephone
NR	new radio (5G)
NR-ARFCN	NR absolute radio frequency channel number
OFDM	orthogonal frequency division multiplexing
P-SS	primary synchronization signal
PA	power amplifier
PBCH	physical broadcast channel
PDCCH	physical downlink control channel
PDSCH	physical downlink shared channel
PML	perfectly matched layer
PoI	point of investigation
PRACH	physical random access channel
PRB	physical resource block
RAT	radio access technology (2G, 3G, 4G or 5G)
RB	resource block
RBW	resolution bandwidth
RE	resource element
RF	radio frequency
RMS	root mean square
RRC	radio resource control
RS	reference signal
Rx	receiving
S-SS	secondary synchronization signal
SEA	specific energy absorption
SA	spectrum analyser

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Abbreviation	Term
SAR	specific absorption rate
sd	standard deviation
SSB	synchronization signal block
TCP	transmission control protocol
TDC	technology duty-cycle
TDD	time division duplex
TDMA	time division multiple access
TER	total exposure ratio
TETRA	terrestrial trunked radio
TM	transmission mode
TRP	total radiated power
TS	transmission scheme
UDP	user datagram protocol
UE	user equipment
UL	uplink
UMTS	universal mobile telecommunications system
USDC	United States digital cellular
VBW	video bandwidth
WCDMA	wideband code division multiple access
Wi-Fi®[2)]	wireless fidelity
WiMAX	worldwide interoperability for microwave access
X-pol	cross-polarization

5 How to use this document

5.1 Quick start guide

Given the different evaluation methods of determining human exposure from EMF, and their inherent complexities, this document contains a significant amount of technical detail. While such detail is necessary, care has been taken to layer the presentation of information, with content broadly separated into process, detail, and additional information. The quick start guide outlined in Figure 1 and Table 1 provides an overview of the evaluation process.

Figure 1 outlines the evaluation process along with the evaluation steps detailed in Table 1. This sequence involves determining the evaluation purpose, method(s) of evaluation, extrapolation, spatial averaging, time averaging and multiple frequency summation as appropriate. The uncertainty and reporting stages complete the evaluation process. A report template is specified in 10.2, and worked case studies are introduced in 5.3.

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2 Wi-Fi® is a trademark of the Wi-Fi Alliance. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC. While officially the term does not have a specific definition, it is typically used to describe Wireless Local Area Networks such as IEEE 802.11b/g/n/ac.

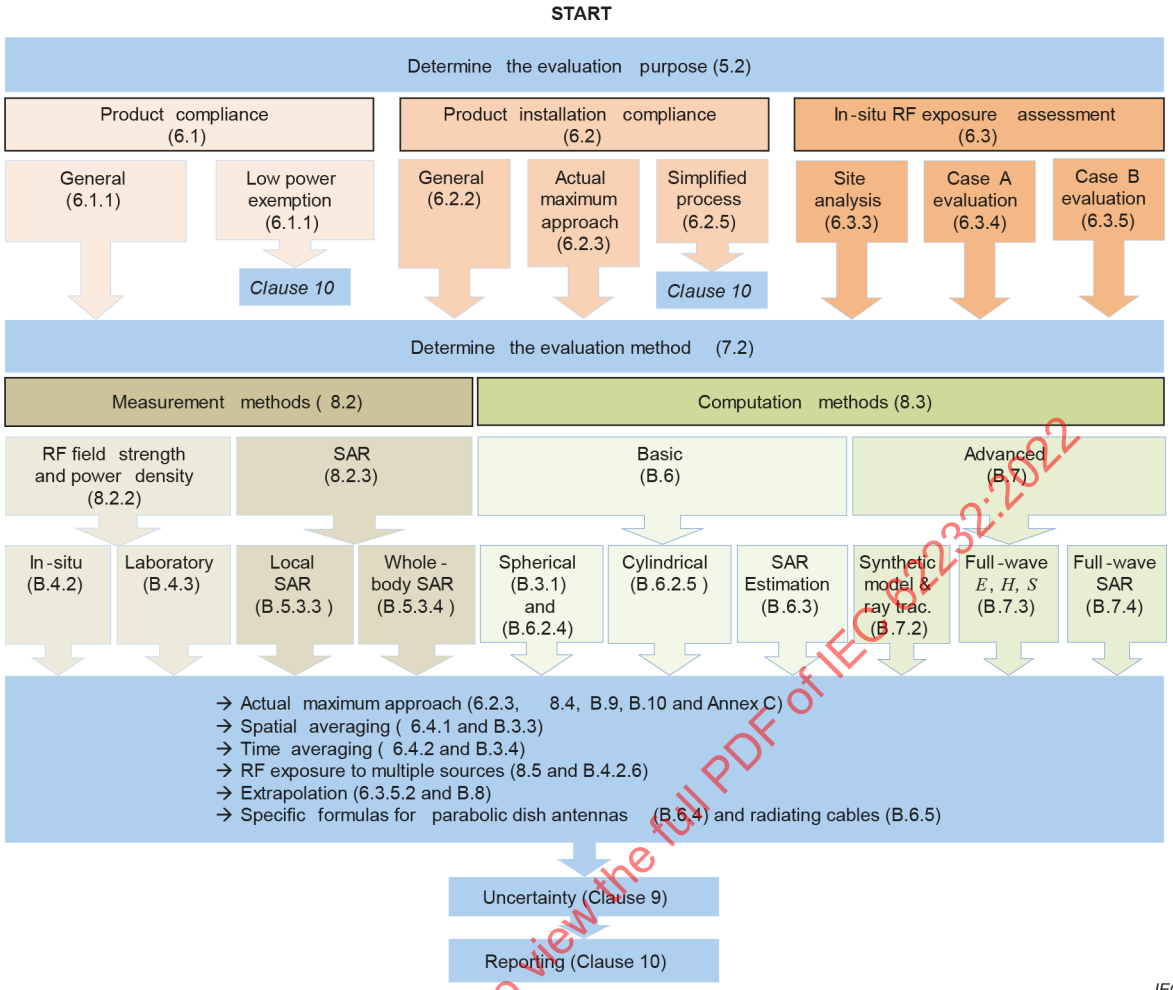


Figure 1 – Quick start guide to the evaluation process

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Table 1 – Quick start guide evaluation steps

Stage	Evaluation steps	Action
Determine evaluation purpose (5.2)	Determine the purpose of the evaluation: – product compliance – product installation compliance, or – in-situ RF exposure evaluation	Confirm purpose of evaluation
RF exposure evaluation process (Clause 6)	Determine the applicable process to be used for the chosen evaluation purpose.	Run the evaluation process
Determine evaluation method (7.1)	Determine if a simplified evaluation process is applicable. Otherwise, select either a measurement or computation evaluation method, or both if required. Evaluation methods are ranked, and in general a higher-ranked method takes precedence. However, lower ranking evaluations are valid within their applicability and can be more practical to implement, depending on cost, feasibility, and resource availability.	Select evaluation method
Measurement (8.2)	Determine applicable measurement procedures: – laboratory or in-situ measurement – SAR, RF field strength (broadband or narrowband) measurements or power density	Select relevant measurement procedures if applicable
Computation (8.3)	Determine applicable computation methods. For example, a simple peak RF field strength evaluation, which is conservative, can be used. Even though higher-ranking evaluation methods shall take precedence, they depend on the detailed information about the source and environment, as well as the availability of software packages capable of modelling such complexities.	Select relevant computation procedures if applicable
Assessment based on the actual maximum approach (8.4)	Determine if an assessment is based on the actual maximum transmitted power or EIRP. Determine if tools for monitoring and/or control tools are required and how they are implemented in accordance with specifications for monitoring counter in 8.4.2 and for control features in 8.4.3 and validation methods using 8.6, Annex B.10 and Annex C.	Select the implementation method based on the actual maximum approach
Extrapolation (B.8)	Determine if extrapolation is required. Where the test configuration differs from the required final evaluation configuration, an extrapolation factor is required to adjust evaluated results (RF field strength, power density or SAR).	Determine extrapolation factor and apply to results
Summation (8.5)	Determine if the evaluation requires summation of combined exposure. Summation of combined RF field strength, power density or SAR value is required either when a single source emits RF fields on multiple frequency bands or when evaluating RF fields from multiple sources.	Sum test results if required
Uncertainty (Clause 9)	Any measurement or computation can only approximate the exposure metric within the uncertainty tolerance, and so a quantitative statement of uncertainty is required.	Determine uncertainty and complete the uncertainty table when applicable
Reporting (Clause 10)	The final report describes the results of the evaluation, provides technical details to allow for repeatability, and interprets the results by comparison with the applicable RF exposure limit, if required.	Prepare the final report

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5.2 RF evaluation purpose categories

This document specifies the three main categories of RF exposure evaluation purpose as follows.

a) Product compliance: determination of compliance boundary information for a BS product before it is placed on the market, see 6.1.

b) Product installation compliance: determination of the total RF exposure levels in accessible areas from a BS product and the resulting compliance boundary information, i.e. compliance distance(s), if any, on the BS installation site taking into account contributions from other relevant sources before the product is put into operation, see 6.2.

c) In-situ RF exposure assessment: measurement of RF exposure levels in the vicinity of a BS installation after the product has been installed and is operating, see 6.3.

Clause 7 provides guidelines on how to select the evaluation method.

5.3 Implementation case studies

IEC TR 62669 [5], contains implementation case studies of typical BS sites to illustrate RF exposure evaluation or assessments for the most common types of BS deployed in mobile and wireless networks, such as small cells, street cells, macro base stations, and parabolic dish antennas used for wireless transmission or mobile backhaul. The lessons learned from each case study lead to recommendations about RF assessment topics to be considered in a subsequent revision of this document. The methodologies and approaches described in [5] are useful for the assessment of early NR BS introduced for consumer trials or deployments.

The implementation case studies in [5] are provided for guidance only and are not a substitute for a thorough understanding of the requirements of this document.

6 Evaluation processes for product compliance, product installation compliance and in-situ RF exposure assessments

6.1 Evaluation process for product compliance

6.1.1 General

A manufacturer is typically required to provide RF exposure information, including relevant compliance boundaries (exclusion zones), to the end user of the product. The compliance boundary (CB) shall be established for the applicable RF exposure limits using RF field strength, power density or SAR assessment methods in accordance with 6.1.2 to 6.1.5. IEC 62479 specifies low power exemption criteria. In circumstances where IEC 62479 is applicable, no compliance boundary is required when a product complies with IEC 62479.

NOTE 1 In this document, the term manufacturer refers to the legal entity intending to place a BS product on the market.

Compliance boundary information is normally determined for one or several selected typical configurations at the rated maximum power and, when relevant, for one or several actual maximum power or EIRP levels, see 6.1.5.1, and assuming free space conditions. Parameters that determine a configuration are, for example, frequency band, bandwidth, access technology, duplexing, antenna, feeder, and information about configurable beams (gain, horizontal beamwidth, vertical beamwidth, EIRP, etc.) for antennas using beamforming.

NOTE 2 Establishing compliance boundaries can be one of a range of requirements or methods that relate to product compliance.

6.1.2 Establishing compliance boundaries

The criteria specified in Table 3 and Clause 8 shall be used to select the exposure metric.

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Depending on the frequency range, SAR or power density measurements are the most appropriate evaluation method to determine the compliance boundary for small stand-alone BS and multi-element BS antennas. For SAR measurements, the largest dimension of the antenna shall be less than or equal to 1,5 m, see 8.2.2 and Clause B.5. Examples of this type of equipment include medium range, local area, or home BS; see 3GPP TS 25.104 [20], 3GPP TS 36.104 [21]. Alternatively, SAR can be calculated using estimation formulas or using advanced computational methods, see B.6.3 and B.7.4, respectively.

For all BS products, in particular wide area and medium range BS, see 3GPP TS 25.104 [20], 3GPP TS 36.104 [21], RF field strength or power density evaluations are applicable. Either laboratory measurements or computations can be used, see B.4.3, Clause B.6 and Clause B.7.

6.1.3 Iso-surface compliance boundary definition

The most accurate (smallest) compliance boundary is obtained as an iso-surface. The 3D iso-surface boundary is described by the locations around the antenna where exposure just equals the applicable RF exposure limit value, see Figure 2.

In this case the shape of the compliance boundary shall be accurately described, e.g. in terms of a mathematical function $z = f(x,y)$.

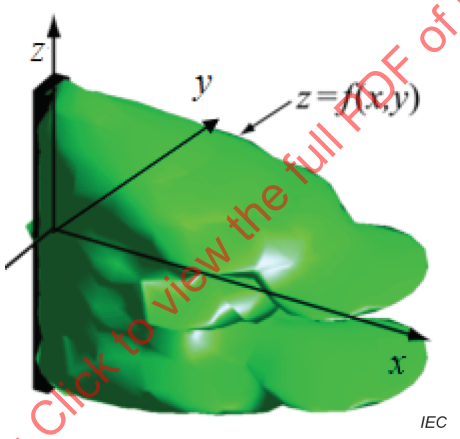


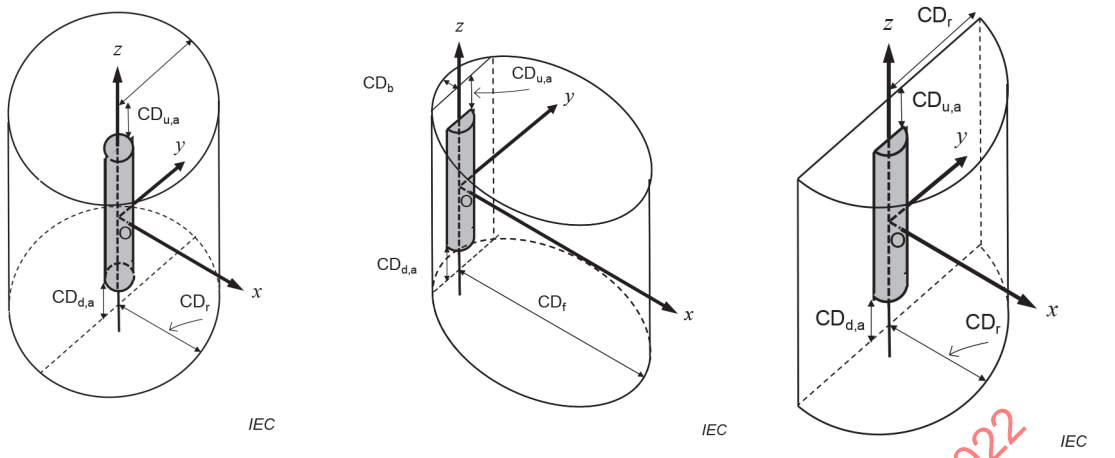
Figure 2 – Example of iso-surface compliance boundary

6.1.4 Simple compliance boundaries

The iso-surface compliance boundary specified in 6.1.3 can be enclosed in simpler shaped volumes described by a set of compliance distances (CD) to provide more conservative compliance boundaries. Valid compliance boundary shapes are not limited to these examples.

In Figure 3 a), b) and c), circular cylindrical, elliptical cylindrical and half-pipe compliance boundaries, respectively, are illustrated for a sector coverage antenna and a colinear omnidirectional antenna.

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a) Colinear omnidirectional antenna – circular cylindrical boundary

b) Sector coverage antenna – elliptical cylindrical boundary

c) Sector coverage antenna – half-pipe boundary

Figure 3 – Example of cylindrical and half-pipe compliance boundaries

The compliance boundary for the sector coverage antenna is described in terms of CD_f, CD_b, $CD_{d,a}$, $CD_{u,a}$, and the antenna length and thickness in accordance with Figure 3. Note that for the sector coverage antenna the distances CD_f and CD_b shall be determined so that the aforementioned iso-surface is completely inscribed by the cylinder. In a similar way, the compliance boundary for the horizontally omnidirectional antenna is described in terms of CD_r, $CD_{d,a}$, $CD_{u,a}$, and the length and radius of the antenna.

NOTE Subscript " $CD_{*,a}$" indicates that the distance is measured from the EUT antenna boundary. Other distance references can also be taken, for example from the centre of the panel. In this case, the subscript " $CD_{*,c}$" of the EUT antenna is also used. See more about antenna reference point in B.2.1.

The box shaped compliance boundary shown in Figure 4 can be used for directional antennas, for example a panel antenna. In this case the boundary is described in terms of CD_f, CD_b, $CD_{d,a}$, $CD_{u,a}$, $CD_{s,a}$, and the dimensions of the antenna.

In order to take into account the horizontal beamwidth of the antenna, the box shape can be truncated with 45° cut plane on the edges near the panel antenna. The truncated box shaped compliance boundary is described in Figure 5, which includes the truncation distance CD_t in addition to the parameters of the box shaped compliance boundary, see Figure 4.

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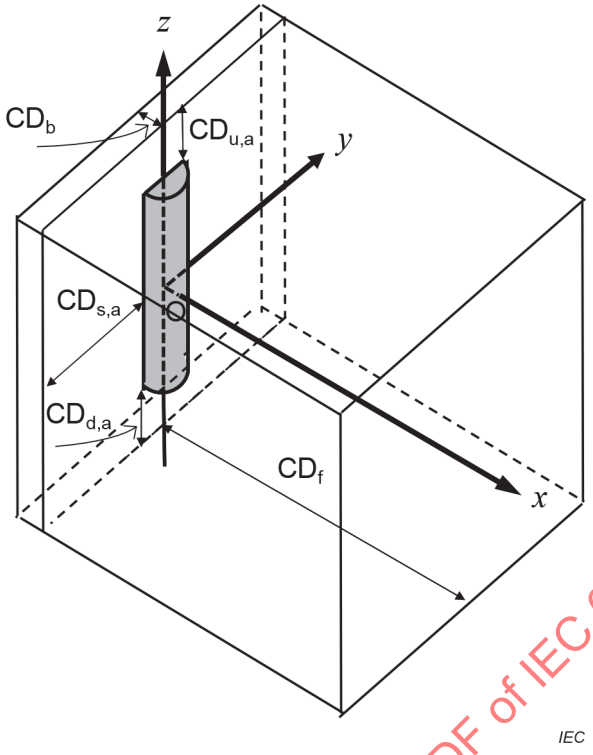
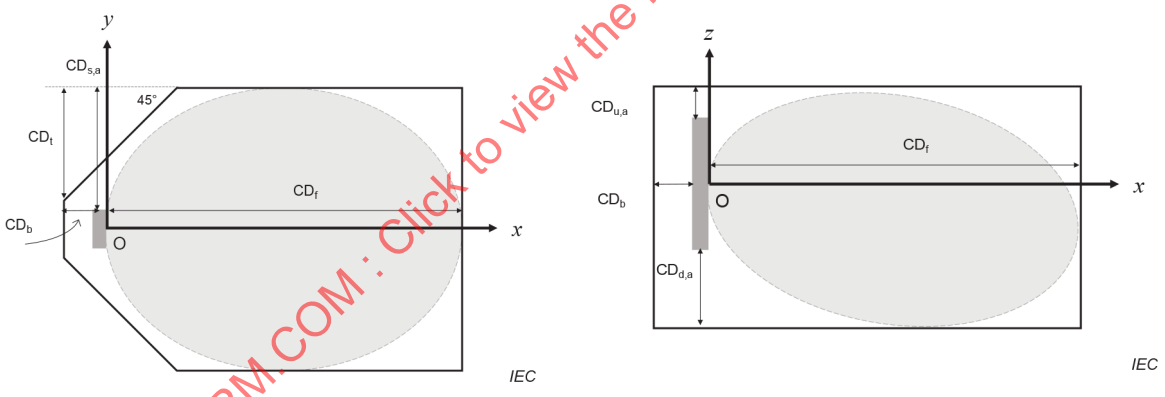


Figure 4 – Example of box shaped compliance boundary



a) Top view b) Side view

Figure 5 – Example of truncated box shaped compliance boundary

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6.1.5 Methods for establishing the compliance boundary

6.1.5.1 General

The compliance boundary shall be established in accordance with 6.1.5.2 to 6.1.5.8 using evaluation methods specified in Clause 8 and Annex B.

The compliance boundary shall be evaluated for:

a) the rated maximum power or EIRP, see 8.6; and

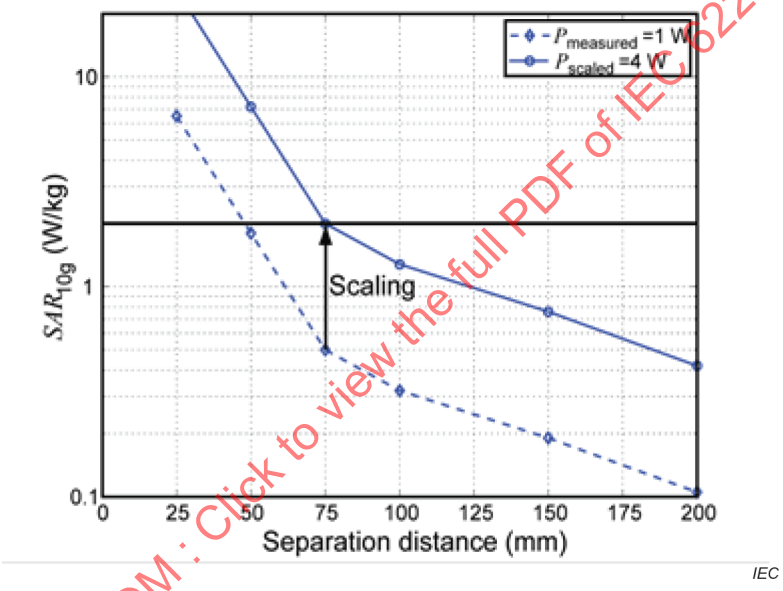
b) one or more actual maximum transmitted power or EIRP value(s) using a power reduction factor if the equipment that is put on the market is able to implement the actual maximum approach specified in 6.2.3, 8.4 and Clause B.9.

6.1.5.2 Establishing compliance boundary using RF field strength or power density measurements

Compliance boundaries specified in 6.1.4 shall be generated by measuring the RF field strength in suitable directions with respect to the transmitting antenna (e.g. front, back, side, and above and below). Then the obtained RF field strength shall be compared with the applicable RF exposure limits (RF field strength or power density), see B.4.3. Scaling is applicable as specified in 6.1.5.3.

6.1.5.3 Establishing compliance boundary using SAR measurements

Compliance boundaries specified in 6.1.4 shall be generated by measuring SAR for suitable antenna orientations as a function of distance using the measurement procedure in Clause B.5 and by comparing the results with the applicable exposure limits. Compliance distances for different power levels shall be obtained by use of linear scaling of the SAR versus separation distance curve as illustrated in Figure 6.



NOTE Scaling to determine the compliance distance at a power level of 4 W, when the SAR measurements were performed at a power level of 1 W for a peak spatial-average SAR (psSAR) exposure limit of 2 W kg^{-1} over an averaging mass of 10 g.

Figure 6 – Example illustrating the linear scaling procedure

The scaled SAR values are computed from the measured values by multiplying the measured values with the ratio between the scaled and the measured power levels. The compliance distance is then obtained from the figure by determining where the scaled SAR curve intersects with the pertinent SAR limit value.

6.1.5.4 Establishing compliance boundary using cylindrical and spherical formulas

The power density or RF field strength shall be calculated in a region surrounding the BS antenna using the basic computation methods specified in B.3.1 and Clause B.6. Based on this evaluation, compliance boundaries in the form of various solids as described in 6.1.4 (cylinder or box) can be determined.

Alternatively, the advanced computation methods described in Clause B.7 can be used to obtain an iso-surface compliance boundary by using the applicable RF exposure limit as the iso-surface value. Simpler and more conservative compliance boundaries can be obtained by inscribing the obtained iso-surface within various solids as discussed in 6.1.4.

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6.1.5.5 Establishing compliance boundary using full wave analysis

Provided that an accurate numerical model has been created following the procedure in B.7.3 and B.7.4, the RF field strength, power density or the SAR from the BS antenna shall be calculated. An iso-surface compliance boundary can then be obtained in a post-processing step by using the applicable RF exposure limit as the iso-surface value. Simpler and more conservative compliance boundaries can be obtained by inscribing the obtained iso-surface in various solids as discussed in 6.1.4.

6.1.5.6 Establishing compliance boundary using SAR estimation formulas

Cylindrical compliance boundaries, see Figure 3, shall be generated for sector coverage and horizontally omnidirectional antennas by using the SAR estimation formulas of B.6.3 and applicable RF exposure limits. While the estimation formulas of B.6.3 in front of the antenna are valid from 300 MHz to 5 000 MHz, their applicability for the back and axial directions is limited to the frequency range between 600 MHz and 2 700 MHz.

For sector coverage antennas, the diameter of the cylinder is determined by the compliance distances in the front and back directions together with the antenna thickness, see Figure 3. For omnidirectional antennas, the radius of the cylinder is determined by the main beam compliance distance and the radius of the antenna. The height of the cylinder is obtained by first multiplying the axial compliance distance with a factor of 2 (above and below antenna) and then adding the length of the antenna.

When implementing SAR estimation formulas for box shaped and truncated box shaped compliance boundaries, the SAR formulas specified in B.6.3 shall be used.

6.1.5.7 Establishing the compliance boundary of massive MIMO or beam steering antennas

For BS products equipped with array antennas intended for massive MIMO or beam steering applications, the assessment of the product compliance boundary shall consider all relevant beam gain patterns $G(\varphi,\theta)$ that are configurable on the BS product, including main beam and secondary or grating lobes, and all electric tilt angles. An example of massive MIMO antenna and corresponding beams and envelope patterns are shown in Figure 7.

A box-shaped or truncated box-shaped compliance boundary shall be used for this type of BS product as described in Figure 8.

The assessment of the product compliance boundary shall be performed using any applicable method specified in 8.3 and Clause B.6 such as the simple spherical formula (B.1) or more advanced computational methods such as the synthetic model and ray-tracing algorithms described in B.7.1 or the embedded pattern approach described in E.9.3. Such advanced methods increase the evaluation accuracy in the near-field compared to when the far-field formula is applied. The actual maximum approach specified in 6.2.3 and 8.4 can be considered.

When using a far-field approach, the BS product compliance boundary can be assessed based on the product envelope radiation pattern. If different beam gain patterns are used for traffic and broadcast signals, both these shall be considered in the compliance boundary assessment, and both shall use the appropriate transmitted power split between the traffic and broadcast signals. For 5G NR, the broadcast signal contribution to the RF EMF exposure can be neglected since the fraction of the power is negligible compared to that from traffic signals.

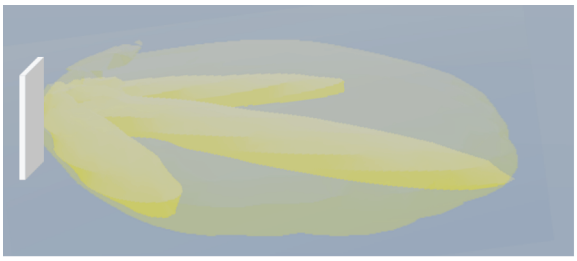
If only the peak antenna gain G_p is known, the analytical method to estimate the compliance boundary for large array antennas described in B.3.1.3 is applicable.

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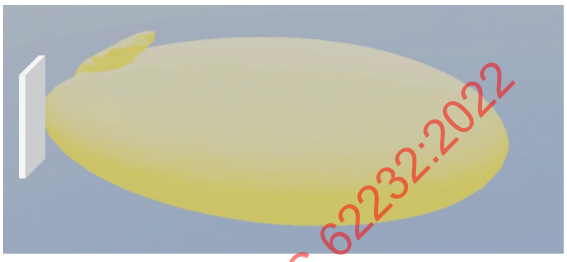
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a) Massive MIMO antenna



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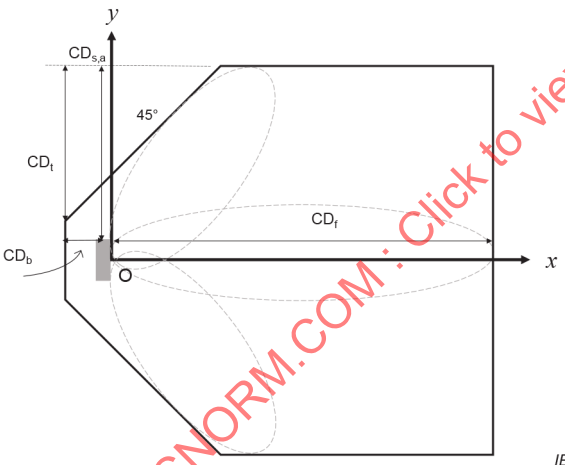
b) 3D beam patterns within the envelope



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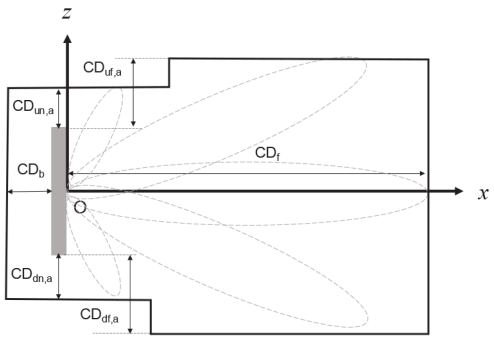
c) 3D envelope pattern including all possible beams

Figure 7 – Example of massive MIMO antenna and corresponding beams and envelope patterns



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a) Top view



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b) Side view

Figure 8 – Example of compliance boundary shape for BS antennas with beam steering

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6.1.5.8 Establishing compliance boundaries for parabolic dish antennas

The compliance boundary is a cylinder, and the compliance distance shall be established using the formula specified in B.6.4. The cylindrical compliance boundary parameters are described in Figure 9.

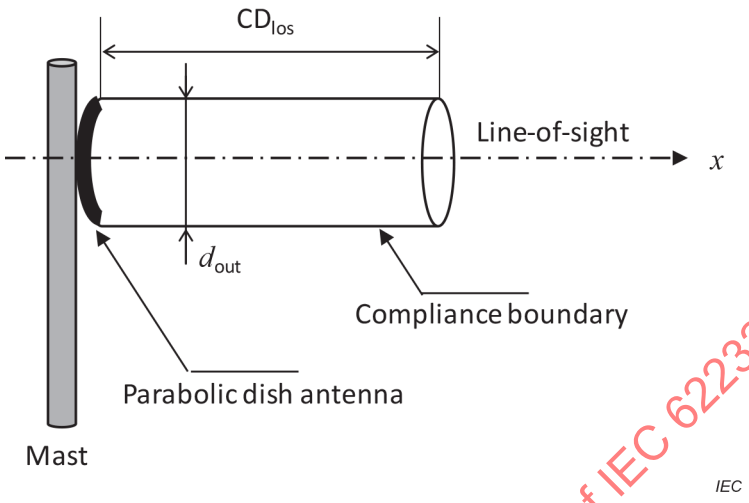


Figure 9 – Example of dish antenna compliance boundary

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6.1.6 Uncertainty

Uncertainty analysis shall be performed in accordance with Clause 9.

6.1.7 Reporting for product compliance

Reporting shall be performed in accordance with Clause 10. The RF exposure assessment report used for product compliance shall contain at least the following.

a) Description of the EUT:

   1) name, identifying reference (e.g. serial number), mobile technologies and list of transmit frequency bands;
   2) for each transmit frequency band, the rated transmitted power or EIRP and, when relevant, one or more actual maximum transmitted power or EIRP value(s) using a power reduction factor if the equipment that is put on the market is able to implement the actual maximum approach specified in 6.2.3 and 8.4;
   3) for each transmit frequency band, antenna characteristics (gain, horizontal and vertical beamwidth, total EIRP) or information about RF parameters (gain, horizontal beamwidth, vertical beamwidth, EIRP, product envelope radiation pattern) for BS antennas using beamforming;
   4) if the product is used with external antennas, a detailed description of at least one typical configuration [3], including antenna system (transmission lines, filters, diplexers, connectors, splitters, combiners, etc.).

[3] Actual product installation parameters are reported according to 6.2.10.

b) Description of the evaluation method and the exposure metric (SAR, S, E or H), the rationale for this choice, see Clause 7, and the relevant technical information required for repeatability and documentation of the validity of the method, including the following:

   1) for measurements:

      i) probe(s) and measurement instrument(s) used, including characteristics, calibration details, and probe correction factors;

      ii) results of a system validation check;

      iii) test setup and measurement conditions (ambient temperature, etc.);

   2) for calculations:

      i) name and software version of the calculation/simulation tool (if applicable);

      ii) inherent limitations of the calculation/simulation tool (e.g. frequency range, near-field/far-field, etc.);

   3) uncertainty analysis.

c) Description of the compliance boundary:

   1) compliance boundary shape, see 6.1.4 and 6.1.5;

   2) compliance distance(s) for the relevant range of RF transmit powers, frequency bands, technologies and applicable exposure limits.

d) Description of monitoring and/or control tools, if applicable.

e) Description of installation guidelines for the EUT, where relevant.

6.2 Evaluation process used for product installation compliance

6.2.1 General

Before a BS product is put into operation, a network operator needs to evaluate the total RF exposure levels in accessible areas from a BS product and the resulting compliance boundary information, i.e. compliance distance(s), if any, on the BS installation site taking into account contributions from other relevant sources. These evaluations are performed to verify RF exposure compliance with the applicable RF exposure limits and regulations. Inside the domain of investigation (DI), see 6.2.6, contributions from other relevant sources and possible effects of the environment shall be considered, including but not limited to collecting characteristics of the ambient fields according to B.4.2.6.

NOTE In 6.2, the term "network operator" refers to the legal entity intending to put a BS product into operation.

The RF exposure levels from the BS product and other relevant sources, and the resulting compliance distance(s), if any, shall be determined using:

a) either the configured maximum power; or

b) the actual maximum threshold power or EIRP as specified in 6.2.3 and 8.4.

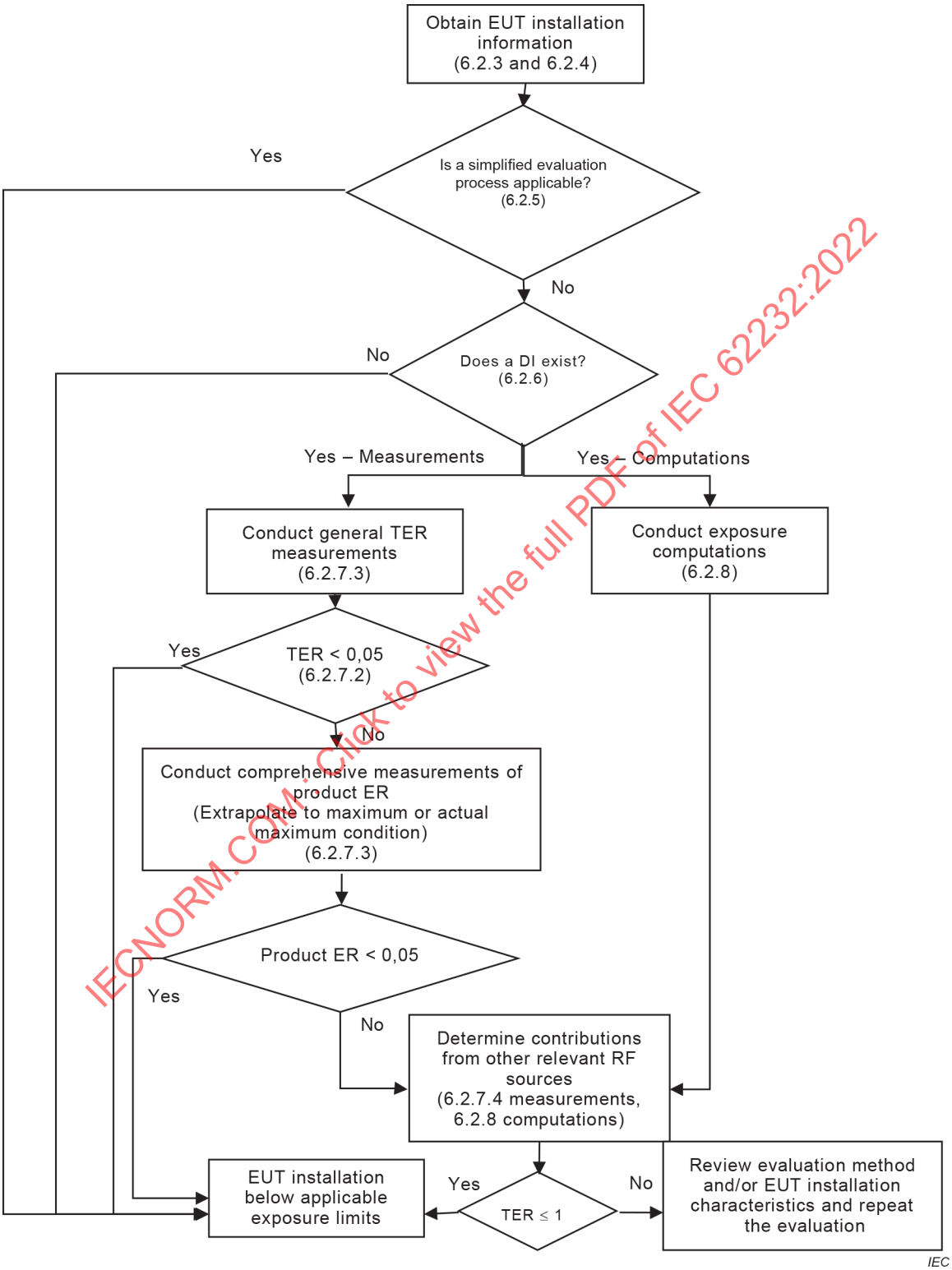
The assessment of RF exposure levels shall be performed using measurements, see B.4.2, or computations, see Clause B.6. Contributions from multiple sources shall be determined using summation formulas, see 8.5.

6.2.2 General evaluation procedure for product installations

Where a new product is installed, the procedure described in Figure 10 shall be used to evaluate the RF exposure levels in accessible areas from the BS and the resulting compliance distance(s), if any, on the BS installation site taking into account other RF sources in the vicinity. This procedure also applies when significant changes are made to the configured parameters of an installed BS.

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In order to allow for accurate and efficient evaluations, different methods are possible. This depends on the characteristics of the product installation. In some specific cases, a simplified evaluation process of the product installation is possible without the necessity of conducting measurements or computations. Such a simplified evaluation process is specified in 6.2.5.



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NOTE It is possible that applicable regulations consider different TER or ER criteria (e.g. 0,01 instead of 0,05).

Figure 10 – Flowchart describing the product installation evaluation process

6.2.3 Product installation compliance based on the actual maximum transmitted power or EIRP

6.2.3.1 General requirements

The actual transmitted power of a BS during operation is generally less than the product of the configured maximum power and the technology duty-cycle factor (F_{TDC}), see IEC TR 62669 [5] and [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34]). Using the actual maximum transmitted power or EIRP approach for compliance assessments avoids an unrealistic overestimation of exposure.

When the actual maximum approach is implemented, the operator (or the legal entity intending to put the product into operation) shall verify that either the actual maximum power threshold(s), P_{act}, or the actual maximum EIRP threshold(s), $EIRP_{act}(\varphi,\theta)$, is/are not exceeded during operation using 8.4.2 and 8.4.3. This applies to a BS sector, cell or segment(s) for massive MIMO operation, see Figure 19. When the actual maximum power threshold(s) for P_{act} or $EIRP_{act}(\varphi,\theta)$ are used instead of the configured maximum power to evaluate RF exposure, this shall be clearly identified and documented in the product installation compliance evaluation report, see 6.2.10.

6.2.3.2 Detailed process

6.2.3.2.1 General

Product installation compliance based on the actual maximum transmitted power or EIRP threshold shall be implemented in two phases. Phase 1 (6.2.3.2.2) applies before putting the BS into operation or when any significant changes are made to the configured parameters of the BS. Phase 2 (6.2.3.2.3) applies when the BS is in operation, see 6.2.3.2.2.

The implementation process for product installation compliance based on the actual maximum approach is shown in Figure 12.

6.2.3.2.2 Phase 1 – before putting the BS into operation or when any significant changes are made to the configured parameters of the BS

Step 1 (6.2.3.2.2 a)) and step 2 (6.2.3.2.2 b)) are based on a methodology using the cumulative distribution function (CDF) of the linear values of actual transmitted power or EIRP (i.e. in W, not dBm). If the CDF is not available or known, the network operator shall move to step 3 (6.2.3.2.2 c)).

a) Step 1 – Evaluate the CDF

   The network operator evaluates the CDF of the actual transmitted power or EIRP of a BS sector, cell or segment(s) from one or a combination of the following approaches:

   1) from measurements on a single BS sector, cell or segment(s) with a similar configuration and environment, see 8.4, Clause B.9 and examples in 13.3 of IEC TR 62669:2019 [5];
   2) from measurements on a representative sample of BS sites deployed by the network operator with similar configurations and environments;
   3) from computational models of either the BS itself or BS sites with similar configurations and environments, see 8.4, Clause B.9 and examples in 13.2 of IEC TR 62669:2019 [5];
   4) from measurements on the BS itself (per sector, cell or segment) in pre-operation (e.g. using simulated traffic).

   NOTE When a new technology is in its infancy and measurement data is limited, computational models can be an appropriate approach for evaluating the CDF.

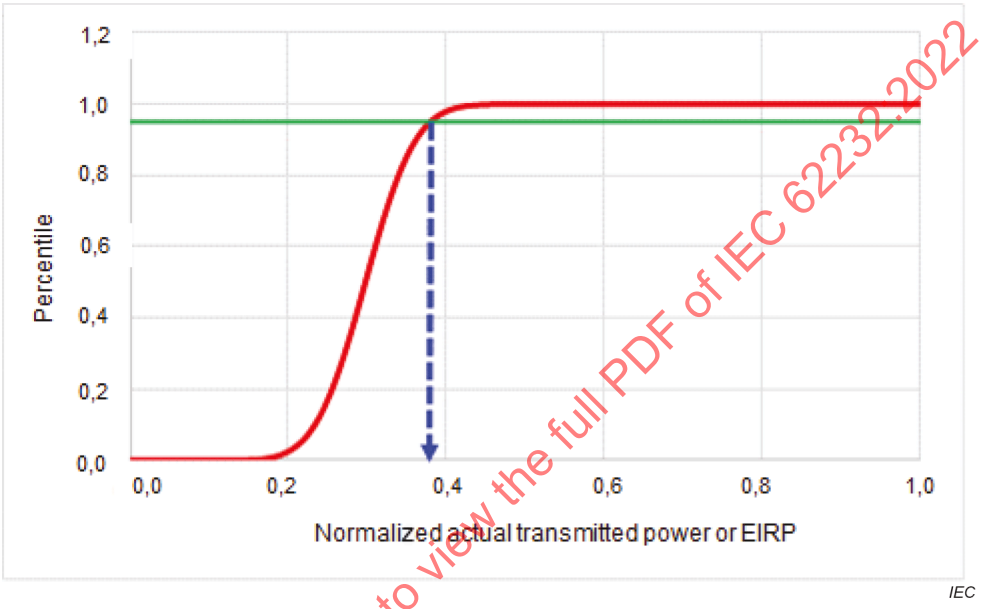
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b) Step 2 – Select the percentile applicable to identify the actual maximum threshold, the network operator selects the percentile (e.g. 95th percentile) of the CDF, see Figure 11, applicable to identify the actual maximum power or EIRP threshold(s) to be used in the RF exposure evaluation and can be configured on the BS based on the following hierarchy:

1) use the percentile as specified in the applicable regulation;

2) otherwise, use a percentile that is deemed appropriate by the network operator.

This percentile is used to determine an appropriate threshold. It does not suggest that the actual transmitted power or EIRP exceeds that threshold for some percentage of the time. As detailed in step 4 (Phase 1 6.2.3.2.2 d)) and step 5 (Phase 2 6.2.3.2.3 a)), actions are taken to ensure that this threshold, once determined and implemented, is not exceeded during BS operation.



NOTE The horizontal axis is normalized to the configured maximum transmitted power or EIRP multiplied by the technology duty-cycle factor (F_{TDC}).

Figure 11 – Example of a CDF curve representing the normalized actual transmitted power or EIRP

c) Step 3 – Determine the actual maximum transmitted power or EIRP threshold(s)

For each BS sector, cell or segment, the network operator shall either:

1) determine the actual maximum transmitted power or EIRP threshold(s) from the percentile of the CDF selected in step 2 (6.2.3.2.2 b)), or

2) if the CDF is not known or available prior to the BS being in operation, use the actual transmitted power or EIRP threshold(s) determined to obtain the given compliance boundary at a site.

Exposure in accessible areas in the vicinity of the BS, see 6.2.1, shall remain less than or equal to the applicable exposure limits when the control feature is activated using configured actual maximum transmitted power or EIRP threshold(s), or when such thresholds are monitored during operation.

Before putting the BS into operation or if any significant changes are made to the configured parameters which result in an increase of the RF exposure levels, the network operator shall re-evaluate the RF compliance boundary based on the resulting actual maximum transmitted power or EIRP threshold(s) as determined in step 3 (6.2.3.2.2 c). The network operator records and reports the updated assessment parameters, results and CDF(s) (if applicable).

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d) Step 4 – Set the BS configured power and power reduction parameters

The network operator shall set the BS configured power and, if applicable, the power reduction parameters per sector, cell or segment such that the actual transmitted power or EIRP does not exceed the actual maximum transmitted power or EIRP threshold(s) specified in Step 3 (6.2.3.2.2 c) during operation.

6.2.3.2.3 Phase 2 – when the BS is in operation

There are two steps applicable to implement the actual maximum approach when the BS is in operation.

a) Step 5 – Monitor and/or control the actual transmitted power or EIRP

When implementing control features (e.g. actual transmitted power or EIRP threshold mechanisms), the network operator shall follow the requirements in 8.4 and Clause B.9.

The network operator monitors the actual transmitted power or EIRP counters per BS sector, cell or segment, see B.9.5, made available by the BS management system to the network operator and records the CDF(s) periodically. The reporting of CDF records is done depending on applicable regulation (e.g. every 7 days).

NOTE 1 It is possible that logging of the actual transmitted power, EIRP and other BS operational details necessary to demonstrate the implementation of the actual maximum approach is required by the applicable regulation.

When power or EIRP monitoring counters or control functions are implemented by the network operator, the reporting of the CDF(s) and/or counters can be optional provided that they have been validated in accordance with Annex C.

NOTE 2 It is possible that applicable regulations require the implementation of both monitoring counters and control functions.

b) Step 6 – Change to BS configured parameters or the actual maximum transmitted power or EIRP threshold(s)

If the network operator intends to change the BS configured parameters impacting the compliance boundary (e.g. configured maximum power) or the actual maximum transmitted power or EIRP threshold(s), the RF compliance boundary shall be updated using step 3 (6.2.3.2.2 c)). It is possible that the applicable regulation requires the appropriate authorities to be informed.

The implementation process for product installation compliance based on the actual maximum approach is shown in Figure 12.

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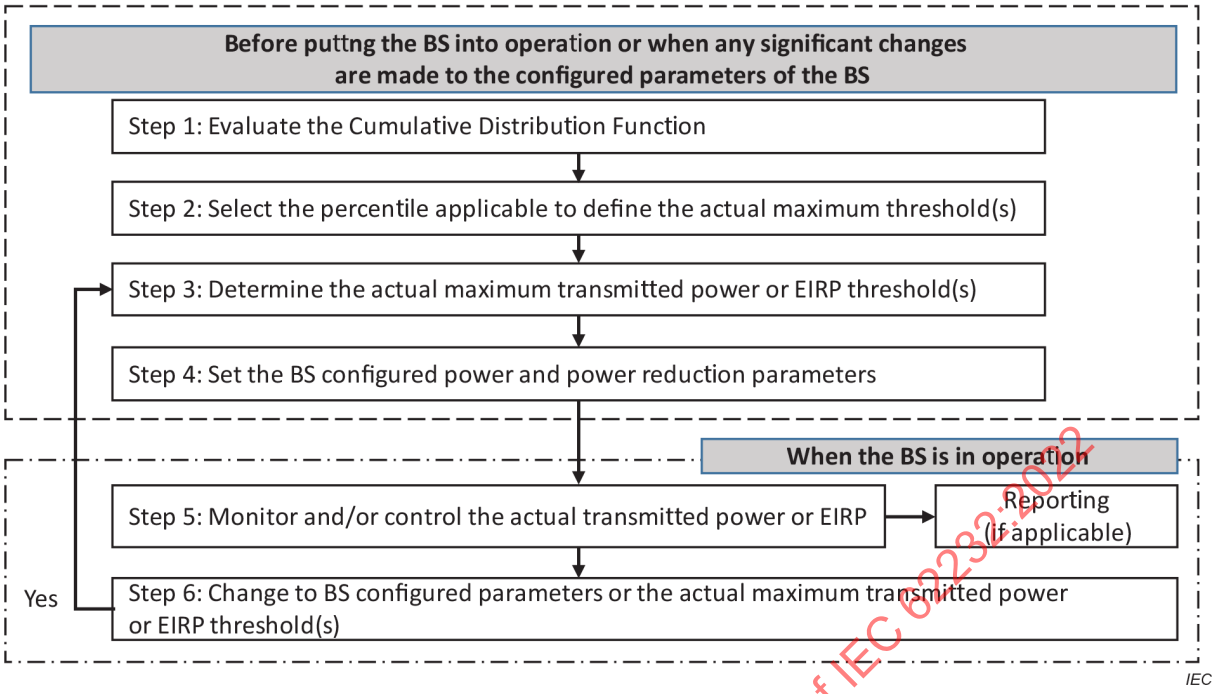


Figure 12 – Flow chart for product installation compliance based on the actual maximum transmitted power or EIRP threshold(s)

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6.2.4 Product installation data collection

a) The following information shall be obtained for the product installation:

1) configured maximum transmitted power for each transmit frequency band of the base station as installed;

2) antenna characteristics (gain, horizontal and vertical beamwidth) for each transmit frequency band, total EIRP, and a detailed description of the configuration of the base station in its operational environment, including antenna system (feeders, connectors, combiners, etc.). If the product installation compliance has been assessed using the simplified evaluation process as specified in 6.2.5, then all parameters used to identify the installation class in Table 2 shall be included;

3) information about the segment grid applied on the BS site with massive MIMO or beam steering antennas;

4) information about the applicable power reduction factor(s) per sector, cell or segment if the product installation compliance is based on the actual maximum transmitted power or EIRP specified in 6.2.3 and 8.4;

5) area where the general public or workers can have access.

b) When evaluations supporting extrapolation to maximum traffic are performed, see Clause B.8, the following information is required:

1) the reference name (e.g. BCCH, CPICH, PDCCH, RS, SSB, CSI-RS) and frequency/bandwidth of any component of the whole signal which is to be used as a reference for extrapolation;

2) the ratio between the component power or EIRP level and the maximum power or EIRP of the configuration to be extrapolated;

3) for example, the following information shall be used for GSM, WCDMA, LTE and NR BS:

i) GSM: centre frequency of the broadcast channel (BCCH) and maximum number of carriers (channels);

ii) WCDMA: common pilot channel (CPICH) frequency and power level relative to total power;

iii) LTE: centre frequency of the EUT used channels and bandwidth, where the used channels include the CRS channel(s) and the boosting factor for the CRS, see E.7.5;

iv) NR: centre frequency of the EUT used channels and bandwidth, where the used channels include the SSB (i.e. PSS, SSS, PBCH and PBCH-DMRS) and CSI-RS channel(s) and the boosting factor for the SSB, see E.8.2.

6.2.5 Simplified product installation evaluation process

A simplified product installation process applies when no detailed measurements or computations are required to establish product installation compliance. The simplified evaluation process is based on easily accessible characteristics of the installation configuration, such as transmitted power or EIRP, see 8.6, direction of the main lobe, compliance boundary, see 6.1, and installation positions of the transmitters/antennas with respect to accessible areas for the product and other relevant sources when applicable.

For the implementation of the simplified evaluation process, product specifications provided by the BS equipment and/or antenna manufacturer(s) shall be used; in particular transmitted power, antenna gain, and compliance distance(s) evaluated in accordance with 6.1.

Product installation evaluation is not required if the product transmitted power complies with IEC 62479, or if the product compliance distance(s) are zero.

For products having an antenna directivity greater than or equal to 30 dBi (e.g. parabolic dish antenna), product installation evaluation is not required provided that there is no access within the compliance distance(s), see B.6.4. For such products, the antenna is usually installed to maintain line of sight conditions in order to prevent the radio link from degrading or becoming unusable.

A simplified installation evaluation process utilizing the product installation class can be developed based on applicable exposure limits, see Figure 13.

The installation classes described in Table 2 can be used when assessing compliance with general public ICNIRP-based exposure limits, see [1] and [2]. The rationales used to establish those classes are presented in Annex D. If there are multiple equipment items collocated at the same site as the product, the EIRP criteria described in Table 2 apply to the sum of EIRP (in W) of all collocated equipment. The EIRP values referenced in Table 2 correspond to the configured maximum EIRP or the configured actual maximum EIRP threshold(s) if the BS is implementing the actual maximum approach specified in 6.2.3 and 8.4.

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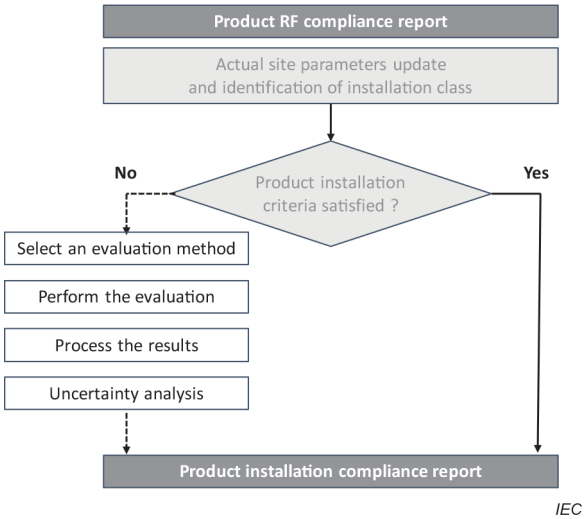


Figure 13 – Simplified compliance assessment process using installation classes

Table 2 – Example of product installation classes where a simplified evaluation process is applicable (based on ICNIRP general public limits [1] and [2])

Instal. class	EIRP[a] (W)	EIRP (dBm)	Product installation criteria
E0	n/a	n/a	The product complies with IEC 62479 or the product compliance distance(s) are zero. No specific requirement for product installation.
E2	≤ 2	≤ 33	The product is installed in accordance with instructions from the manufacturer and/or entity putting into operation. Compliance with the exposure limits is generally obtained at zero distance or within a few centimetres.
E10	≤ 10	≤ 40	The product is installed in accordance with instructions from the manufacturer and/or entity putting into operation and the lowest radiating part of the antenna(s) is at a minimum height of 2,2 m above the walking or standing surface accessible by the general public.
E100	≤ 100	≤ 50	The product is installed in accordance with instructions from the manufacturer and/or entity putting into operation and: a) the lowest radiating part of the antenna(s) is at a minimum height of 2,5 m above the walking or standing surface accessible by the general public; b) the minimum distance to areas accessible to the general public in the main lobe direction is CD_m [b], and c) there is no pre-existing RF source with EIRP above 10 W installed within a distance of 5 × CD_m metres in the main lobe direction (as determined by considering the half power beam width) and within CD_m metres in other directions. CD_m is the compliance distance in the main lobe assessed in accordance with 6.1. If CD_m is not available, a value of 2 m can be used or 1 m if all product transmit frequencies are greater than or equal to 1 500 MHz.[c]
E+	> 100	> 50	The product is installed in accordance with instructions from the manufacturer and/or entity putting into operation and: a) the lowest radiating part of the antenna(s) is at a minimum height of h_m metres above the walking or standing surface accessible by the general public, b) the minimum distance to areas accessible to the general public in the main lobe direction is CD_m [b] metres, and c) there is no pre-existing RF source with EIRP greater than 100 W installed within a distance of 5 × CD_m metres in the main lobe direction and within CD_m metres in other directions. CD_m is the compliance distance in the main lobe assessed in accordance with 6.1 and h_m is given by Equation (1), Equation (2), Equation (3), and Equation (4).[d]

[a] EIRP transmitted by the installed antenna(s) including all active bands.

[b] CD_m is also described as CD_f or CD_r in 6.1.4. For E10, the installation height is derived from the SAR estimation formula provided in B.6.3 and realistic antenna configurations. For E100, the installation height is derived from the SAR estimation formula provided in B.6.3 and realistic antenna configurations and CD_m values of 1 m and 2 m are derived from the classical spherical formula (Equation (B.7)) using a ground reflection factor of 0. For E+, h_m and CD_m specified in Equation (1), Equation (2) or Equation (3) are derived from the classical spherical formula (Equation (B.7)) using a ground reflection factor of 1. For E+ in the millimetre frequency range, h_m and CD_m specified in Equation (4) are derived from the synthetic model method (Equation (B.54)) using a metallic ground reflection, see B.7.1 and Clause D.6.

[c] When such condition is not fulfilled, the installation is still compliant if the sum of the EIRP values of the EUT and nearby sources is less than 100 W. If the total EIRP is greater than 100 W then the EUT is still compliant if it is installed at a minimum height of h_m metres above the walking or standing surface accessible by the general public and at a minimum distance from areas accessible to the general public in the main lobe direction of CD_m metres, where h_m and CD_m are obtained using Equation (1), Equation (2), Equation (3) or Equation (4) for the sum of the EIRP including those of nearby sources.

[d] When this condition is not fulfilled, the installation is still exempted from evaluations if the EUT is installed at a minimum height of h_m metres above the walking or standing surface accessible by the general public and at a minimum distance from areas accessible to the general public in the main lobe direction of CD_m metres, where h_m and CD_m are obtained using Equation (1), Equation (2), Equation (3) or Equation (4) for the sum of the EIRP values including those of nearby sources.

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The frequency dependent Equation (1), Equation (2), and Equation (3) are applicable for calculation of the minimum installation height h_m and the compliance distance in the main lobe CD_m described in Table 2. These equations were introduced in [35] and amended in [36] for millimetre wave frequencies. To be conservative, f shall be chosen to correspond with the lowest exposure limit of all frequency bands of the EUT.

Equation (1) applies for frequencies between 100 MHz and 400 MHz:

$$h_m = \max\begin{cases} 2+\sqrt{\dfrac{EIRP \cdot A_{sl}}{2\pi}} \\ 2+\sqrt{\dfrac{EIRP}{2\pi}}\sin(\alpha + 1{,}129 \times \Delta\theta_{3dB}) \end{cases} \quad \text{and} \quad CD_m = \sqrt{\frac{EIRP}{2\pi}} \tag{1}$$

Equation (2) applies for frequencies between 400 MHz and 2 000 MHz:

$$h_m = \max\begin{cases} 2+\sqrt{\dfrac{200 \times EIRP \cdot A_{sl}}{f \cdot \pi}} \\ 2+\sqrt{\dfrac{200 \times EIRP}{f \cdot \pi}}\sin(\alpha + 1{,}129 \times \Delta\theta_{3dB}) \end{cases} \quad \text{and} \quad CD_m = \sqrt{\frac{200 \times EIRP}{f \cdot \pi}} \tag{2}$$

Equation (3) applies for frequencies between 2 000 MHz and 300 000 MHz (i.e. 300 GHz):

$$h_m = \max\begin{cases} 2+\sqrt{\dfrac{EIRP \cdot A_{sl}}{10\pi}} \\ 2+\sqrt{\dfrac{EIRP}{10\pi}}\sin(\alpha + 1{,}129 \times \Delta\theta_{3dB}) \end{cases} \quad \text{and} \quad CD_m = \sqrt{\frac{EIRP}{10\pi}} \tag{3}$$

where

f is the frequency of operation of the BS in MHz;

A_{sl} is the side lobe suppression value specified in a linear scale;

α is the downtilt in radians (both electrical and mechanical);

$\Delta\theta_{3dB}$ is the vertical half power beamwidth in radians.

Alternatively, in accordance with [36] and Clause D.6, for BS using massive MIMO or beam steering antennas operating between 10 000 MHz and 300 000 MHz (i.e. 300 GHz) Equation (4) applies:

$$h_m = \max\begin{cases} 2+\sqrt{\dfrac{EIRP \cdot A_{sl}}{65\pi}} \\ 2+\sqrt{\dfrac{EIRP}{65\pi}}\sin(\alpha + 1{,}129 \times \Delta\theta_{3dB}) \end{cases} \quad \text{and} \quad CD_m = \sqrt{\frac{EIRP}{40\pi}} \tag{4}$$

where symbols are the same as in Equation (3).

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NOTE For BS installed at 2,5 m above the walking or standing surface accessible by the general public, h_m and CD_m values in Equation (4) remain unchanged when considering ground reflections, see Clause D.6.

6.2.6 Assessment area selection

The domain of investigation (DI) represents the volume where an exposure evaluation and assessment shall be performed. The DI is the part of the assessment domain boundary (ADB) of the equipment under test (EUT) where there is access. Access in this context refers to any part of the body being within the ADB under normal conditions.

NOTE Outside the ADB the product is not a relevant source, and an evaluation is not needed.

If the product compliance boundary, as specified in 6.1, is available, the ADB length L_{ADB} (in metres) in the main beam direction shall be five times the compliance distance. Alternatively:

a) for a single band antenna, the simplified expression provided in Equation (5) can be used for ADB length. It is based on the free-space formula (Equation (B.7)) and provides a conservative estimation of the ADB in the shape of a box (Figure 14).

$$L_{ADB} = \sqrt{\frac{EIRP}{0{,}05 \times 4\pi \cdot S_{lim}}} = 1{,}3 \times \sqrt{\frac{EIRP}{S_{lim}}} \quad (5)$$

where S_{lim} is the applicable power density exposure limit (W m^{-2}).

b) for multiband antennas having more than one active band, the ADB length can be calculated using Equation (6).

$$L_{ADB} = 1{,}3 \times \sqrt{\sum_i \frac{EIRP_i}{S_{lim,i}}} \quad (6)$$

where $EIRP_i$ is the EIRP of the product in band i and $S_{lim,i}$ is the applicable power density exposure limit (W m^{-2}) for band i.

The dimensions of the ADB, if determined using Equation (5) or Equation (6), are largely overestimated in the vertical direction of the antenna. Therefore, the following rules shall be applied:

1) Access regions placed h_b metres or more below the antenna mounting height (measured from the centre point of the antenna) shall not be considered as part of the ADB, where h_b is given by Equation (7) [4]

$$h_b = \max\left(L_{ADB} \cdot \tan\alpha\,;\ 3{,}5\right) \quad (7)$$

where α is the antenna downtilt (mechanical and electrical) in radians.

For fixed beam antennas, if α is unknown it can be assumed to equal $\pi/15$ radians (12°), which is a realistic maximum downtilt chosen to obtain a conservative result. The number 3,5 m was also chosen to correspond to a realistic maximum h_b for an antenna without

[4] The first term in brackets corresponds to the height of the ADB given by the main beam for down-tilted antennas. The second term takes into consideration that for small tilt angles, the ADB in the vertical direction might be given by the antenna side lobe (or by the extension of the main lobe in the vertical plane). Since the maximum side lobe amplitude and direction might be difficult to estimate, a minimum height of 3,5 m is conservatively chosen.

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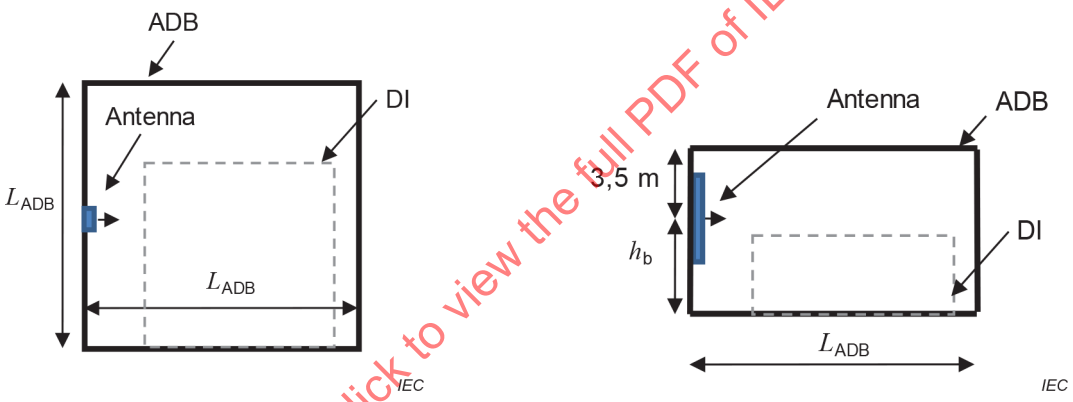
downtilt. For massive MIMO or beam-steering antennas, α corresponds to the maximum downtilt (including mechanical downtilt) among the available beams considering the configured beam-steering range of the BS product in the elevation plane.

2) General public access regions placed 3,5 m or more above the antenna mounting height (measured from the centre point of the antenna) shall not be considered as part of the ADB.

Equation (5) and Equation (6) are applicable for down-tilted antennas. If the antenna is tilted upwards the values shall be reversed. For BS product installations able to steer the beam above the horizon, h_b as provided by Equation (7) applies both below and above the antenna installation height. In addition, for rooftop or wall installations, regions within the building on which the antenna is mounted shall be excluded from the ADB if the antenna main beam is pointing away from the building[5].

Based on observations of the product installation, the environment, and experience gained from RF exposure evaluations of similar sites, the DI can be restricted to the points of maximum exposure.

Where general public access to the ADB is restricted, there is no DI and therefore the product installation is compliant for general public access.



a) Top view **b) Side view**

NOTE The ADB is oriented in accordance with the antenna direction.

Figure 14 – Example of DI within a square-shaped assessment domain boundary (ADB) with dimension L_{ADB}

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6.2.7 Measurements

6.2.7.1 General

RF field strength measurements by means of frequency selective or broadband equipment or both can be used to evaluate the product installation. The measurement system(s) and the post processing shall, at a minimum cover the frequency range envisioned by the evaluation from 100 kHz to 6 GHz and up to 300 GHz if required. Measurement equipment shall be chosen and operated in accordance with B.4.2.

Measurement contributions from multiple sources shall be summed in accordance with 8.5 in order to assess the total exposure ratio (TER).

5 Transmission in these directions corresponds to the side lobe of the antenna. In addition, the attenuation due to the walls, roof, etc can reduce the power density by 10 dB to 20 dB or more.

6.2.7.2 General TER measurements

General TER evaluation consists of measurements over the whole DI of the total RF field strength or power density over the entire frequency range of the product and any relevant sources that are external to the product. Broadband equipment is suitable for this type of measurement. Frequency selective equipment can be used provided that the RF field strength is integrated over the entire relevant frequency range.

During general TER evaluation, measurements shall be taken in accordance with B.4.2.5 over the whole DI.

The BS installation is assessed to be compliant without further investigation if the maximum time averaged measured TER is less than or equal to 0,05 within the DI. If the measurement equipment does not have a shaped frequency response, the lowest electric field strength or power density exposure limit values in the frequency range used by the entire BS installation shall be used to calculate TER.

NOTE It is possible that applicable regulations consider a different measured TER criterion (e.g. 0,01 of the measured TER).

Otherwise, a comprehensive TER measurement shall be performed in accordance with 6.2.7.3.

6.2.7.3 Comprehensive product ER measurement

The comprehensive product ER measurement shall be performed at the location(s) of maximum TER identified in the general TER evaluation. It takes into account time averaging in the same way as TER. It is performed in order to obtain a conservative estimate of the TER when the product is transmitting at configured maximum power.

The comprehensive product ER measurement shall be performed using broadband or frequency selective measurement equipment that is in compliance with the requirements and the measurement procedures specified in B.4.2.

For comprehensive measurements, the extrapolation procedure as described in Clause B.8 shall be applied and spatial averaging shall follow 6.4. Where the product ER obtained with comprehensive measurements is less than 0,05 no further evaluation is required, and the product installation is assessed to be compliant.

NOTE It is possible that applicable regulations consider a different ER criterion (e.g. 0,01).

6.2.7.4 Exposure contribution of ambient sources

Ambient sources shall be identified in accordance with the description in 7.2 and in 8.5.

For evaluations where the extrapolation of the RF field strength to the maximum power has been obtained by means of broadband measurements in accordance with B.8.2, the contribution from ambient sources is implicitly evaluated. No additional measurements need to be performed.

Sources that are not relevant can be excluded.

If the operating bands of nearby ambient sources are known, the ER contribution of each source can be determined. This can be done using frequency selective equipment by integrating the RF field strength over the corresponding band. When this information is not directly available, it can be retrieved by inspection of the significant spectrum peaks measured by the frequency selective equipment.

For time variant signals, the RF field strength from relevant source contributions shall be scaled to maximum power, see Clause B.8, or actual maximum power or EIRP when the equipment is able to implement the approach specified in 6.2.3 and 8.4. If the extrapolation factors are unknown the power density for each of the relevant bands shall be measured. Such

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measurement should occur during high-traffic hours, using a max-hold trace for a time until the equipment reading stabilizes. However, additional uncertainty associated with not actually scaling to maximum power should be appropriately accounted for in the uncertainty evaluation, see Clause 9.

6.2.8 Computations

Various computational methods can be used to evaluate the level of exposure within the DI, see Clause B.6. An overview of the applicability of the methods is provided in Table 7.

The transmitted power of the BS shall conservatively be assumed as equal to the maximum power or the actual maximum power if the BS is implementing the actual maximum approach specified in 6.2.3, 8.4 and Clause B.9). Ambient fields from relevant sources within the DI shall be included in the evaluation. The effect of environmental reflectors and scatterers shall be considered where relevant, in accordance with B.4.2.6. In areas with environmental reflectors a modified free space approach can be applied. In this case the ER is first overestimated by using the ER estimated in free space, and this free space estimate is then multiplied by a compensating factor. Alternatively, the effect of reflecting objects shall be included in the uncertainty budget.

Reflections can be modelled using calculation tools, such as ray tracing, see B.7.1. For ground reflections, a multiplication factor of 2,56 (for power density) or 1,6 (for E-field strength) can be applied to free space computed values as recommended in [37]. These multiplication factors do not always apply to reflections from rooftop sites. Other site-specific power density multiplication factors can be used where more detailed information is available. In general, an accurate estimation of these reflection factors requires information on site topography including material parameters of nearby structures, frequency, transmission bandwidth and field polarization.

A reflecting structure can be excluded from the RF exposure computations if one or more of the following conditions apply.

- The reflecting structure is not within line of sight from both the evaluation point and the radio source.
- The geometry of the reflector, evaluation point and radio source is such that the reflected ray is directed away from the evaluation point.
- The maximum projected dimension of the reflecting structure in the direction of the evaluation point is less than L_{max} from Equation (8)

$$L_{\text{max}} = \sqrt{\frac{d}{\lambda}} \tag{8}$$

where

d is the distance from the radio source to the structure;

λ is the wavelength of the considered radio source.

NOTE A structure can be considered a reflector at a given frequency but not necessarily at other frequencies.

6.2.9 Uncertainty

Uncertainty analysis shall be performed in accordance with Clause 9.

The target expanded uncertainty is less than or equal to 4 dB, which is considered industry best practice. The expanded uncertainty for the RF exposure evaluation used for the product installation compliance assessment shall not exceed 6 dB. Under this condition, the evaluation result shall be compared directly to the exposure limit. However, the entity performing the uncertainty analysis also needs to be aware of the applicable regulation.

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6.2.10 Reporting for product installation compliance

Reporting shall be performed in accordance with Clause 10. The RF exposure evaluation report used for product installation compliance shall contain at least the following.

a) Description of the product:
   1) name, identifying reference (e.g. serial number), wireless technologies, and list of transmit frequency bands;
   2) for each transmit frequency band, either the configured maximum power or the actual maximum threshold value if the BS is implementing the actual maximum approach specified in 6.2.3 and 8.4;
   3) for each transmit frequency band, antenna characteristics (gain, horizontal and vertical beamwidth, total EIRP) or information about configured beams and their RF parameters (gain, horizontal beamwidth, vertical beamwidth, horizontal and vertical beam steering range, EIRP, configured envelope radiation pattern, broadcast and/or traffic radiation pattern envelope whatever represents the maximum exposure for the installed BS) for antennas using beamforming, and, if the product is used with external antennas, a detailed description of at least one typical configuration, including antenna system (transmission lines, filters, diplexers, connectors, splitters, combiners, etc.);
   4) if the product installation compliance has been assessed using the simplified evaluation process as specified in 6.2.5, then all parameters used to identify the installation class in Table 2, see 6.2.5, shall be included.
b) Description of installation configuration for the product, including installation height, etc.
c) Implementation of the simplified product installation evaluation method (rationale, outcome) if applicable.
d) If the simplified product installation evaluation is not applicable, additional technical information required for repeatability and for documentation of the validity of the method are required. This shall include a description of the evaluation method and the exposure metrics (TER, S, E or H), the rationale for the choice, see 7.1, as well as:
   1) description of the domain of investigation, relevant sources and scatterers;
   2) spatial averaging method used;
   3) for measurements:
      i) probe(s) and measurement instrument(s) used, including characteristics and calibration details;
      ii) testing conditions (temperature, etc.);
   4) for calculations:
      i) name and version of the software simulation tool (if applicable),
      ii) calculation and simulation parameters used;
   5) validity of measurement and/or calculation results;
   6) uncertainty analysis.
e) Description of the monitoring counters and/or control tools as well as CDF report(s) used as part of the actual maximum approach if applicable.
f) Description of the applicable compliance distance(s) and general public access restrictions, if any, and guidelines on how to comply with occupational limits during installation, maintenance and repair of the product.

The documentation can cover several base stations with similar technical specifications and environmental conditions.

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6.3 In-situ RF exposure evaluation or assessment process

6.3.1 General

In-situ measurements are performed for multiple objectives, such as:

a) to determine if the RF exposure levels from the EUT and ambient sources are in compliance with applicable regulations or exposure limits, as observed or extrapolated to maximum or actual maximum levels; or

b) to obtain the RF exposure levels for use when presenting results even if they are well below the applicable exposure limits.

Accomplishing these objectives with in-situ measurements requires broadband (Case A) and/or frequency selective (Case B) evaluation. Case A evaluation shall be performed as specified in 6.3.4 to provide an evaluation of total in-situ RF exposure levels from all sources and frequencies "as observed" without spectrum differentiation. Case B evaluation shall be performed as specified in 6.3.5 to provide a detailed evaluation of in-situ RF exposure levels. Case B evaluation is used when determining the contributions of relevant sources or sources of interest to TER or when performing extrapolation.

Case A and Case B evaluations can be combined, for example, if the outcome of a Case A evaluation is to be compared with the applicable regulations or exposure limits, see Case A in 6.3.4.

6.3.2 In-situ measurement process

The procedure described in Figure 15 shall be used to evaluate or assess in-situ RF exposure.

The process shall start by performing a site analysis to identify all relevant fixed emitting RF source installations in the surrounding area in accordance with 6.3.3. The in-situ RF exposure evaluation shall be performed in the measurement area, see 7.2.2, using the selected exposure metric, see 7.2.3, measurement type (Case A or Case B) and measurement techniques specified in B.4.2 to meet the measurement objectives. In selecting measurement type, the measurement equipment and the post processing shall cover the RF emissions from all sources identified by the site analysis. Finally, uncertainty and reporting shall be completed as specified in 6.3.6 and 6.3.7, respectively.

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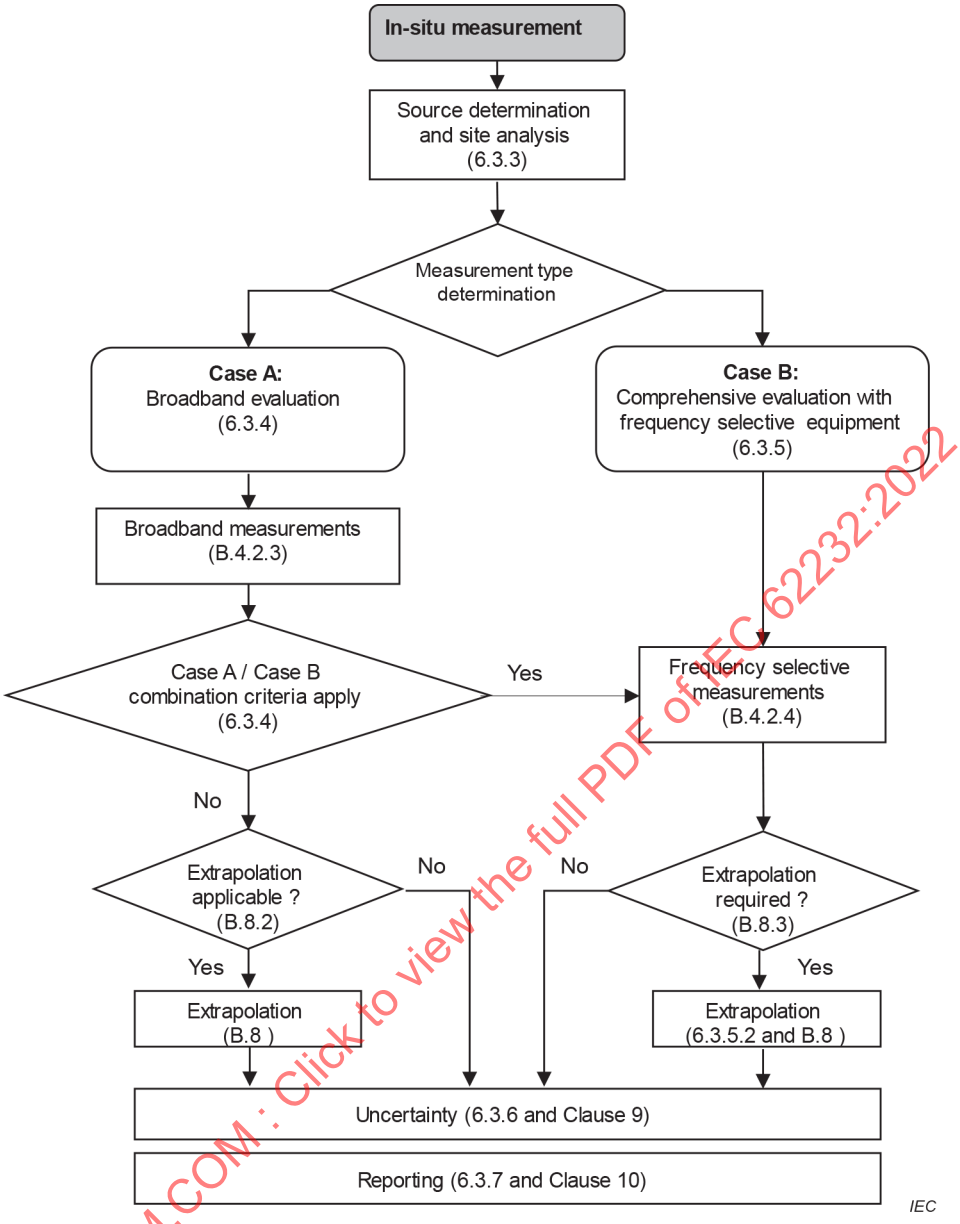


Figure 15 – In-situ RF exposure evaluation or assessment process flow chart

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6.3.3 Site analysis

During the site analysis, the surveyor shall:

a) select the measurement area;

b) identify the position of the EUT with respect to the measurement area, if applicable;

c) check for and document ambient sources according to B.4.2.6;

d) select the exposure metric and the appropriate measurement equipment(s) to cover the frequency range applicable to the EUT and ambient sources.

If the EUT or ambient sources are using beam steering, the purpose of the Case A evaluation remains to provide a global evaluation of in-situ RF exposure levels from all sources and frequencies together "as observed". As all RF sources are not always steering the RF energy towards the evaluation location, it is recommended to have, at a minimum, a UE connected with the EUT using the method described in B.4.2.5.4.

Additional guidelines are provided in Clause 7 and Annex A.

6.3.4 Case A evaluation

Case A corresponds to an exposure evaluation on one measurement area using broadband equipment in compliance with 8.2.2. and B.4.2.3 and consistent with the objective as described in 6.3.1.

The measurement system(s) shall cover the frequency range of the RF emissions from the EUT and all relevant ambient sources between at least 100 kHz and 300 GHz as determined by the site analysis. Additional requirements are specified in B.4.2.2.

A Case A evaluation shall start by performing a slow scan over the measurement area at a height of 1,5 m above the walking or standing surface in order to find the location of the maximum RF exposure, i.e. the point of investigation (PoI). At this evaluation location, if spatial averaging is required, measurements at different heights shall be performed in order to assess the spatial averaged value as specified in 6.4.1. If time averaging is required, it shall be implemented as specified in 6.4.2.

It is recommended to complement a Case A evaluation with a Case B evaluation, see 6.3.5, if the following criteria apply:

a) the outcome of a Case A is above the applicable regulations or exposure limits at the PoI in order to perform the detailed calculation of the TER taking into account all contributors; or

b) the outcome of a Case A at the PoI is intended to be extrapolated, compared with the applicable regulations or exposure limits, and the measured power density is above a fixed value of 100 mW m^{-2} (or equivalent E-field strength or H-field strength) or above a certain threshold derived from the applicable exposure limit (e.g. 50 % of the limit expressed in power).

Extrapolation using a broadband probe is not recommended and shall only be performed under the conditions specified in B.8.2.

6.3.5 Case B evaluation

6.3.5.1 Measurement protocol

Case B corresponds to a comprehensive exposure evaluation with frequency selective equipment, including identification of relevant sources, see 6.2.1, or sources of interest, and extrapolation of exposure to configured maximum transmitted power or EIRP or to the actual maximum power or EIRP if required.

The measurement shall be performed using frequency selective equipment as specified in 8.2.2 and B.4.2.4. Case B measurements shall be performed at a given location, e.g. the PoI identified in Case A evaluation, see 6.3.4. The TER shall be evaluated in accordance with 8.5.

The evaluation shall begin at the PoI with a comprehensive frequency scan covering at minimum the frequencies of ambient signals documented in the site analysis, see 6.3.3. The outcome of the comprehensive frequency scan shall be used to identify any source of interest frequencies for which spatially averaged, see 6.4.1, or sweeping, see B.4.2.5.2, measurements, shall be performed. If no source of interest is identified, the two highest measured RF sources shall be measured.

Frequency selective measurements shall be performed at all points required for the implementation of spatial averaging or sweeping method. Depending on the objective of the in-situ evaluation or assessment, either the raw measurement results or the extrapolated measurement result, in accordance with 6.3.5.2, shall be provided.

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6.3.5.2 Extrapolation of the configured maximum or actual maximum RF exposure

If the aim is to evaluate the maximum RF exposure conditions taking into account traffic, transmitted power and beam steering (e.g. massive MIMO) variations, then the evaluation result data shall be extrapolated. Extrapolation shall apply only to sources of interest, see 6.3.5.1.

Extrapolation shall be performed from measurement of stable (i.e. time independent) reference signal(s) or channel(s) as specified in B.8.3 and Annex E. In the context of this document, stable means that the RF source reference signal or channel variability is ±10 %. Other recommendations can be found in system specifications (e.g. 3GPP 38.104 [17] for NR).

The extrapolation factor shall be evaluated as specified in Clause B.8 based on

a) either the configured maximum transmitted power or EIRP, or
b) the actual maximum transmitted power or EIRP value(s) configured in the BS if the actual maximum approach is implemented as specified in 6.2.3 and 8.4.

6.3.6 Uncertainty

Uncertainty analysis shall be performed in accordance with Clause 9.

The target expanded uncertainty is less than or equal to 4 dB, which is considered industry best practice. The expanded uncertainty for RF exposure evaluation used in in-situ RF exposure assessment shall not exceed 6 dB. Under this condition, the evaluation result shall be compared directly to the exposure limit. However, the entity performing the uncertainty analysis also needs to be aware of the applicable regulation.

6.3.7 Reporting

Reporting shall be performed in accordance with Clause 10. The in-situ RF exposure evaluation or assessment report shall contain at a minimum:

a) a description of the measurement site, including the relevant sources and the points or locations where measurements have been performed;
b) the environmental conditions, time and date, name of entity responsible for the measurement;
c) the measurement protocol used, including spatial averaging, time averaging, method used to deal with beam forming systems, etc.;
d) the probe(s) and measurement instrument(s) used, including characteristics and calibration details and probe correction factors;
e) the measurement results and all information necessary for the interpretation of the in-situ RF exposure evaluation or assessment (e.g. instantaneous, extrapolation, etc.);
f) if extrapolation is used, a description of the extrapolation method and rationale for the extrapolation factor(s);
g) the uncertainty analysis.

6.4 Averaging procedures

6.4.1 Spatial averaging

Where spatial averaging of RF field strength or power density is required (e.g. 6.3 related to in-situ RF exposure assessment), it shall be performed in accordance with the specifications in B.3.3 and with a minimum of three measurement points as shown in Figure B.7. However, depending on the location and accuracy required, the number of measurement points to be averaged can be increased using B.3.3.2 specifications.

Spatial-peak RF field strength or power density shall also be considered, see Table 3, if required by the applicable RF exposure limits.

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The spatial-averaging procedure applicable to SAR evaluation is described in Clause B.5.

6.4.2 Time averaging

Factors that contribute to time variation include changing propagation conditions, variations of the transmitted power due to traffic load, transmission from the base station in multiple beam directions using beamforming (e.g. massive MIMO), variations due to power control, or transmitter duty-cycle.

Where time averaging is applicable for exposure assessment, it shall be implemented as specified in B.3.4 and Clause B.9. The averaging time T_{avg} is specified in the applicable regulation or exposure limits.

When implementing the actual maximum approach, the actual averaging time T_{avg_act} shall be used for the implementation of monitoring counters and control features as specified in 8.4 and Clause B.9. T_{avg_act} is generally equal to T_{avg}. However, lower values are acceptable. Nevertheless, the entity implementing the actual maximum approach also needs to be aware of the applicable regulations.

7 Determining the evaluation method

7.1 Overview

Once the purpose of the evaluation has been chosen, see 5.2, the next step is to determine the evaluation method including the evaluation points, ambient fields and other details. The evaluation method shall be selected considering the exposure metrics, see 7.2.3, and the applicability of the evaluation methods, see Clause 8 and Table 3. More than one evaluation method can be valid.

If specific evaluation methods are specified in Clause 6, these shall be used. Otherwise, the process in 7.2 shall be followed. The entity determining the evaluation method also needs to be aware of the applicable regulatory requirements.

Evaluation method determination examples can be found in the worked case study examples of IEC TR 62669 [5].

7.2 Process to determine the evaluation method

7.2.1 General

Prior to conducting an evaluation, the surveyor shall determine the evaluation configuration following the tasks described below.

a) Establish the evaluation points in relation to the source-environment plane, see 7.2.2.

b) Establish the appropriate exposure metric, see 7.2.3.

c) Select computation or measurement approach, see Annex A.

d) Establish if ambient fields need to be considered.

e) Where the evaluation purpose is to determine the combined field from all sources at a given location, ambient fields shall be evaluated, see B.4.2.6. The surveyor shall identify all fixed permanently installed RF sources as specified in 6.3.3 and B.4.2.6.

f) Ambient sources can be identified through visual inspection, consultation of available user databases, information from the site owner, as well as broadband or frequency selective measurements.

g) The evaluation shall be performed in accordance with the specifications in 6.2.7.4 or 6.3.2.

h) Additional considerations to consider can be found in Clause A.5.

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The evaluation method is chosen based on the determined evaluation configuration and guidance provided in Clause 8 and Annex B.

7.2.2 Establishing the evaluation points in relation to the source-environment plane

7.2.2.1 General

The source-environment plane describes the regions to be considered in the evaluation point selection; based on environmental complexity and distance from the source.

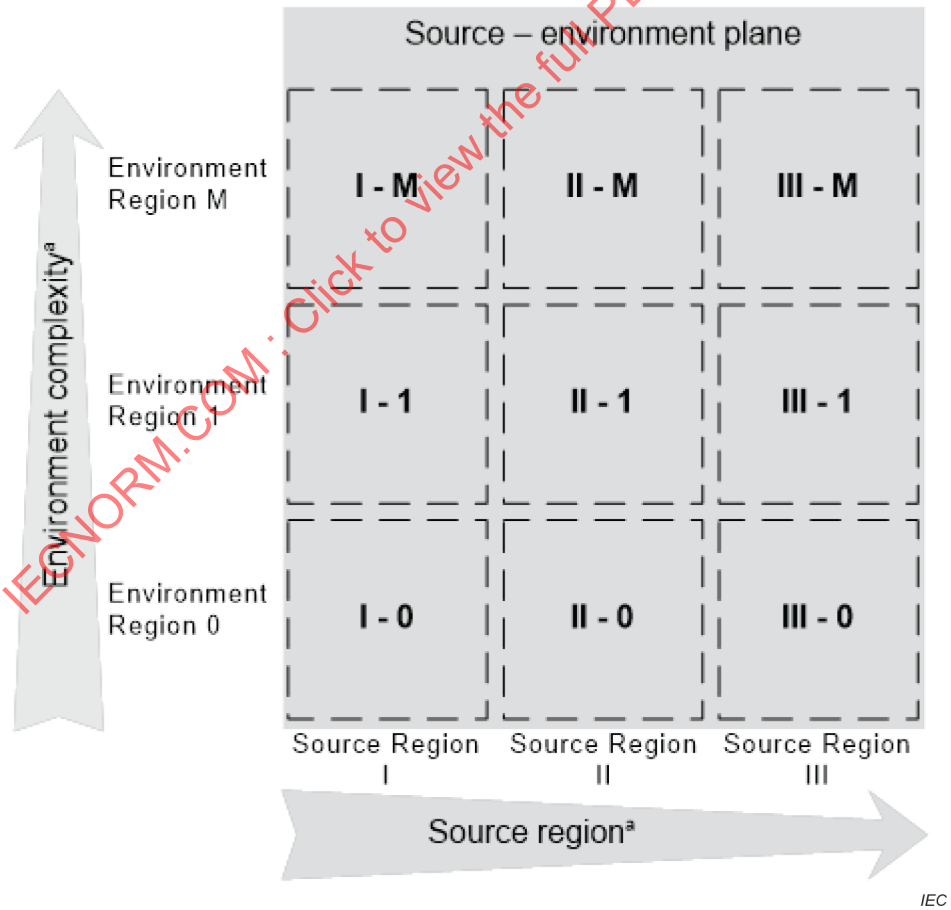
7.2.2.2 Source-environment plane definition

The source-environment plane is a tool developed to categorize the regions around an antenna based on environmental complexity and distance from the antenna. Influenced by both the scattering environment and the distance separating the antenna from the evaluation point, the source-environment classification impacts the evaluation method.

For more detail on the environmental regions, see Annex A.

The source-environment plane consists of nine evaluation regions. The "x-axis" represents increasing distance from a source located at the coordinate-system origin. The "y-axis" represents increasing scattering effects contributing to total fields at observation points, see Figure 16.

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[a] In this document, if a * replaces the environment region character, this means any environment region (i.e. 0, 1 or M) applies. If a * replaces the source region character, it means any source region (i.e. I, II or III) applies.

Figure 16 – Source-environment plane concept

7.2.2.3 Definitions of source regions

Source region I constitutes the reactive near-field of the source, see A.1.3.

Source region II constitutes the radiating near-field of the source, see A.1.3.

Source region III constitutes the far-field of the source, see A.1.3.

7.2.2.4 Definitions of environment regions

Definitions of the environment regions are based on the proximity to, or effects from, scattering objects; such scattering objects can be in the vicinity of the source, in the vicinity of the evaluation point or can otherwise affect the RF field strength between the antenna and the evaluation point.

In environment region 0 there is an unobstructed path between the source antenna and the evaluation point. Also, the levels from any reflections are small enough not to affect materially the evaluated level, within the uncertainty of the evaluation.

In environment region 1 there is an unobstructed path between the source antenna and the evaluation point and there is just one dominant reflector, e.g. the ground. Other reflectors meet the environment region 0 criteria.

In environment region M there is obstruction between the source antenna and the evaluation point and/or there are two or more reflectors.

Examples are provided in A.1.2.

7.2.2.5 Establish where evaluation points are on the source-environment plane

Determine in which source-environment plane regions the evaluation points lie, see Clause A.1.

7.2.3 Exposure metric selection

Exposure metrics shall be selected in accordance with the applicable exposure guidelines. Table 3 describes the exposure metrics (RF field strength, power density and SAR) validity and classification based on where the evaluation point lies in the source-environment plane, see 7.2.2, the availability of assessment methodologies as described in this document and the applicable RF exposure limit. The method with the lowest exposure metric class takes precedence.

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Table 3 – Exposure metrics validity for evaluation points in each source region

Exposure metric class	Exposure metrics validity (Measured/computed)[a]		
	Source region I	Source region II	Source region III
1	SAR up to 6 GHz[b,c] and power density above 6 GHz[c,d]		
2	Electric field strength and magnetic field strength[c,d], or power density[c,e,f]	Electric field strength, or magnetic field strength, or plane wave equivalent power density[c,f]	

[a] The exposure metric can be expressed as a value or exposure ratio.

[b] Some international exposure standards or guidelines provide basic restrictions in terms of SAR also at frequencies higher than 6 GHz (e.g. whole-body SAR limits are applicable up to 300 GHz in accordance with ICNIRP-2020 [1]). However, SAR measurement procedures described in this document are limited to 6 GHz.

[c] Where the applicable exposure limits include a time-averaging period, a relevant time-averaged evaluation has a higher validity than a non-time-averaged evaluation.

[d] Some international exposure standards provide basic restrictions above 6 GHz in terms of absorbed power density. This metric is currently not addressed by IEC 62232. Therefore, (incident) power density (i.e. reference levels), is identified in this table as the class 1 exposure metric above 6 GHz, see also 8.1.

[e] The reactive power components are not negligible in source region I, so both electric field strength and magnetic field strength need to be evaluated, see Clause A.1. For certain frequencies, exposure standards provide reference levels only in terms of power density. In source region I, power density shall be determined based on the assessment of both the electric and magnetic fields. Some exposure standards restrict the validity of power density to source region II and source region III.

[f] The validity of spatial averaging depends on the applicable exposure limit in accordance with three cases (here specified for RF field strength but also applicable to power density):

Case i) The applicable exposure limits include different spatial-peak and spatially-averaged RF field strength limits (both conditions to be met): In this case, the spatially-averaged RF field strength is more appropriate than the spatial-peak RF field strength when comparing with the spatially-averaged limit. However, in the condition when the RF field strength is uniform on the averaging surface, spatial averaging might be redundant, and the spatial-peak value can be conservatively used for direct comparison with both limits. The spatially-averaged RF field strength shall not be compared with the spatial-peak limit.

Case ii) The applicable exposure limits include a single limit addressing both spatial-peak and spatially-averaged evaluations: In this case, the spatial-peak RF field strength is more appropriate than the spatially-averaged RF field strength.

Case iii) The applicable exposure limits include only spatial-averaged values over different areas for localized and whole-body exposure, respectively. In this case, as described in i), the spatially-averaged RF field strength is more appropriate than the spatial-peak, but averaging might be redundant when the RF field strength is deemed uniform on the averaging surface.

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8 Evaluation methods

8.1 General

Clause 8 provides an overview of the evaluation methods to measure or compute RF field strength, power density, SAR, transmitted power or EIRP. The details are provided in corresponding annexes. Each method description includes the applicability and constraints within which it shall be employed, the information required to implement the method, and advice relating to the uncertainty of the evaluation.

The evaluation method is selected in accordance with Clause 7. For additional information, clarification or justification of the evaluation methods, refer to annexes and external references.

Procedures and methods described in this document are used to demonstrate compliance with the applicable exposure guidelines, including the most recent revisions published by ICNIRP-2020 [1] and IEEE Std C95.1-2019 [3]. Such guidelines have introduced new basic restrictions above 6 GHz based on the absorbed/epithelial power density and, for ICNIRP-2020 [1], whole-body SAR for localized and whole-body exposure. While absorbed/epithelial power density is not addressed in this document and whole-body SAR measurement techniques are specified only up to 6 GHz, assessment methodologies valid up to 300 GHz are provided in this document based on evaluation of the (incident) power density and can be used to demonstrate compliance above 6 GHz by means of the reference levels.

Considerations about brief exposure limits specified in ICNIRP-2020 [1] are provided in Annex F.

When deriving RF field strength quantities from power density, attention should be paid that far-field conditions are valid.

8.2 Measurement methods

8.2.1 General

The relevant measurement methods are displayed in Figure 17. This process is an expansion of the measurement block from Figure 1.

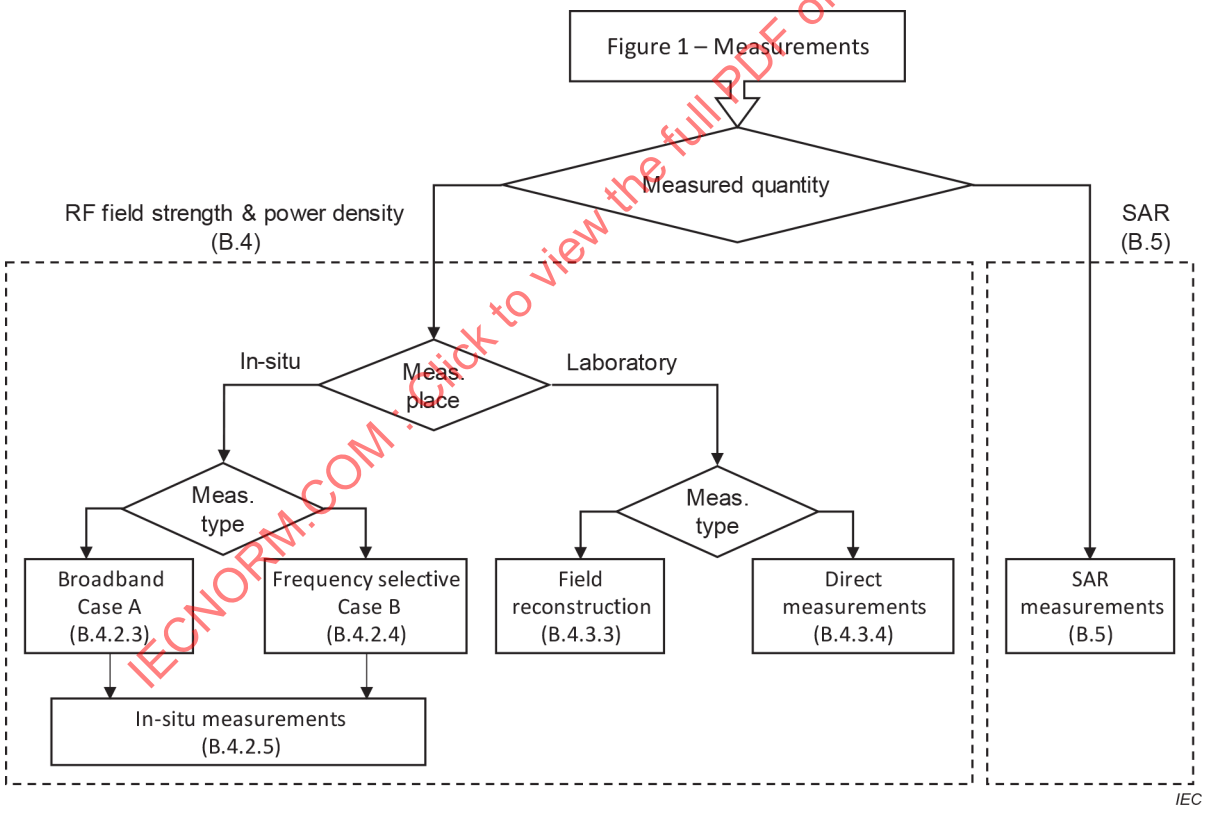


Figure 17 – Flow chart of the measurement methods

8.2.2 RF field strength and power density measurements

RF field strength and power density measurements are applicable in the source-environment plane regions and operating regions described in 7.1 and Table 3, see 7.2.3. The requirements listed in Table 4 shall be applied depending on the evaluation process, i.e. product compliance, product installation compliance or in-situ RF exposure assessment.

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Due to space limitations, laboratory based (electric and magnetic) RF field strength and power density measurement procedures are generally applicable to low power equipment, e.g. equipment with a compliance distance lower than 1 m.

For in-situ measurements, frequency selective measurement equipment is recommended in situations where more than one signal or frequency is present.

NOTE Probes can be mounted on drones for performing measurements in inaccessible areas or in areas where the levels can exceed the exposure limits. General implementation guidelines are provided in IEC TR 62669 [5].

Table 4 – Requirements for RF field strength and power density measurements

Normative subclause	Title
B.4.2	In-situ RF exposure measurements
B.4.3	Laboratory based RF field strength and power density measurements
B.3.3	Spatial averaging
B.3.4	Time averaging
B.4.4	RF field strength and power density measurement uncertainty

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8.2.3 SAR measurements

The SAR measurement procedures are generally applicable for small stand-alone equipment/devices and multi-element base station antennas shorter than or equal to 1,5 m, whether the BS is installed indoor, outdoor or underground (e.g. in a man-hole). The distance between the phantom and the outer surface of the radiating structure (antenna) shall not exceed 1 000 mm. While SAR limits for whole-body exposure might be relevant up to 300 GHz in ICNIRP-2020 [1], SAR measurement procedures specified in this document are applicable in the frequency range 300 MHz to 6 GHz.

In the frequency range relevant to whole-body SAR limits, it is not necessary to perform whole-body SAR evaluation if the maximum transmitted power of the product is less than the values specified in Table 5.

Table 5 – Whole-body SAR exclusions based on RF power levels

Exposure condition	Maximum transmitted RF power (W)
General public exposure.	General public whole-body SAR limit [W kg^{-1}] × 12,5 [kg]
General public exposure. Lowest part of the product antenna installed 2,2 m or more above level realistically accessible by the general public. Access denied to children due to antenna installation height.	General public whole-body SAR limit [W kg^{-1}] × 46 [kg]
Worker's exposure.	Occupational whole-body SAR limit [W kg^{-1}] × 46 [kg]
NOTE 1 The product installation point is measured from the lowest part of the antenna above an area realistically accessible to the general public. The height of 2,2 m is derived from class E10, see Table 2. NOTE 2 The whole-body SAR exclusion power levels have been derived based on the following assumptions: (1) all of the power emitted from the antenna is absorbed in the body, (2) children below the age of 4 do not have access to the antenna at a distance of less than 20 cm and (3) the body masses for a 4-year-old child (12,5 kg) and a 16-year-old worker (46 kg) have been derived from body weight statistics published by WHO [38] and US National Center for Health [39], see B.5.3.4.	

SAR measurements (local or whole-body) shall be performed using the measurement equipment specified in Clause B.5. More specifically:

a) for local SAR measurements, the protocol specified in B.5.3.3 shall be used;

b) for whole-body SAR measurements, the protocol specified in B.5.3.4 shall be used.

SAR measurements shall be performed in accordance with the requirements specified in Clause B.5, in particular the requirements listed in Table 6.

Table 6 – Requirements for SAR measurements

Normative subclause	Title
B.5.2	SAR measurement requirements
B.5.3	SAR measurement description
B.5.4	SAR measurement uncertainty

8.3 Computation methods

The relevant computation methods for RF field strength, power density and SAR evaluation are displayed in Figure 18. This process is an expansion of Figure 1, dividing the evaluation methods into one of two categories, based on their complexity.

When considering which computation method to select, the simplest applicable method should be used provided that it delivers the required level of precision. A more comprehensive (advanced) evaluation method usually takes longer to perform, but yields a more accurate result; as such, an advanced computation takes precedence when compared to the results of a basic evaluation – see the exposure metric class in 7.2.3 and the evaluation method ranking in Table A.12. Table A.10 and Table A.11 provide further guidance on how to select the appropriate computation method.

Each computation method shall be validated before it is used. As a minimum, the described computation methods shall be verified against the results presented in Annex B. For methods or cases not covered in Annex B, validation shall be completed against measured data.

Table 7 provides a summary of applicable computation methods (basic and advanced) in the source-environment plane, see Annex A. RF exposure computation shall be performed in accordance with the requirements specified in Clause B.3.1 and Clause B.6, in particular the requirements listed in Table 8.

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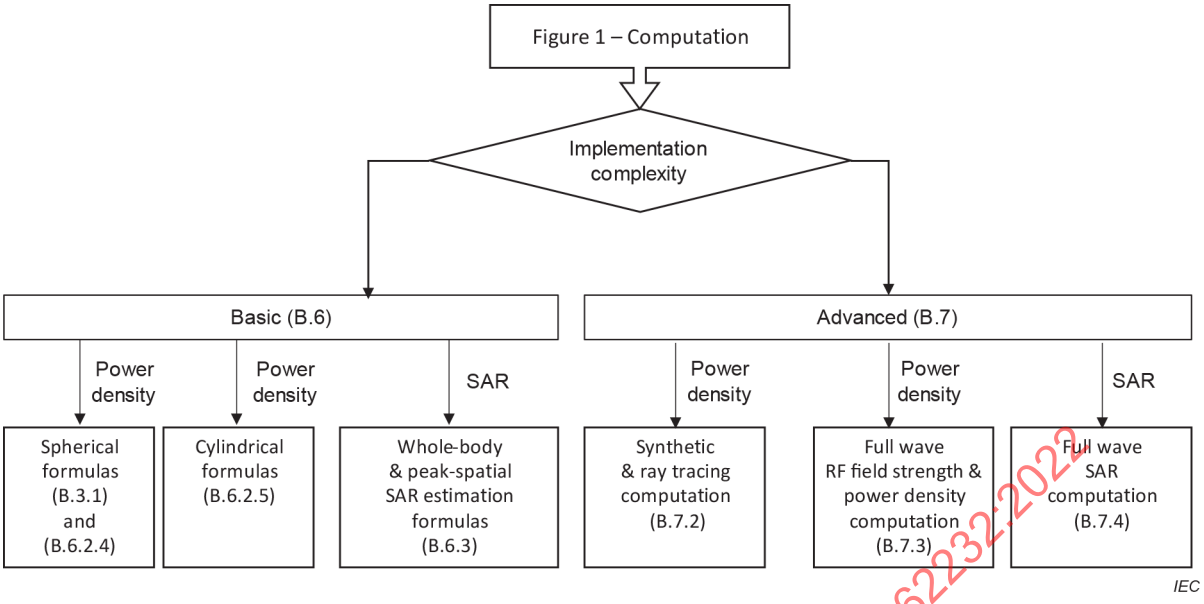


Figure 18 – Flow chart of the relevant computation methods

Table 7 – Applicability of computation methods for source-environment regions of Figure 16

Environment region	Applicable methods[a] (see B.3.1, Clause B.6 and Clause B.7)	
	Source region I	Source regions II and III
M	1. Full wave – RF field strength 2. Full wave – SAR or power density	1. Synthetic model and ray tracing algorithms 2. Full wave – RF field strength 3. Full wave – SAR or power density
1	1. Full wave – RF field strength 2. Full wave – SAR or power density	1. Spherical and/or cylindrical formulas 2. Synthetic model and ray tracing algorithms 3. Full wave – RF field strength 4. Full wave – SAR or power density
0	1. SAR estimation formulas 2. Full wave – RF field strength 3. Full wave – SAR or power density	1. SAR estimation formulas 2. Spherical and/or cylindrical formulas 3. Synthetic model and ray tracing algorithms 4. Full wave – RF field strength 5. Full wave – SAR or power density

[a] Methods are listed in order of recommendation based on the practicality of implementation. As a general principle, however, in the event of dispute methods based on basic restrictions always take precedence over reference level-based methods.

Table 8 – Requirements for computation methods

Normative subclause	Title
B.3.1	Calculation of RF field strength and power density
B.6	Basic computation methods
B.7	Advanced computation methods

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8.4 Methods for assessment based on actual maximum approach

8.4.1 General requirements

The compliance method specified in 6.2.3 relies on the implementation of tools developed by manufacturers based on BS counters to monitor P_{act} or $EIRP_{act}(\varphi,\theta)$ in accordance with 8.4.2 and features to control that P_{act} or $EIRP_{act}(\varphi,\theta)$ values remain below the configured threshold(s) in accordance with 8.4.3.

The assigned actual maximum threshold(s) for P_{act} or $EIRP_{act}(\varphi,\theta)$ is/are set by the network operator (or the legal entity intending to put the product into operation) and shall be clearly identified and documented in the compliance evaluation report. When choosing the time-averaging period considered in 8.4.2 and 8.4.3, the entity implementing the actual maximum approach needs to be aware of the applicable international guidelines or national regulations. The time-averaging period shall be reported.

Guidance for the validation of power or EIRP monitoring counters and control features is provided in Annex C.

NOTE 1 While EIRP is also affected when controlling the transmitted power, $EIRP(\varphi,\theta)$ is mainly used in 8.4 to identify methods where the transmitted power is controlled in by varying azimuth φ and/or elevation θ direction considering the antenna gain $G(\varphi,\theta)$.

NOTE 2 The exposure assessment methodologies described in this document are implemented in fixed locations in order to assess compliance at fixed locations. Actual exposure of a person moving outside of a BS compliance boundary is expected to remain below the exposure limit. Further research is ongoing to support such case study analysis.

8.4.2 Actual transmitted power or EIRP monitoring

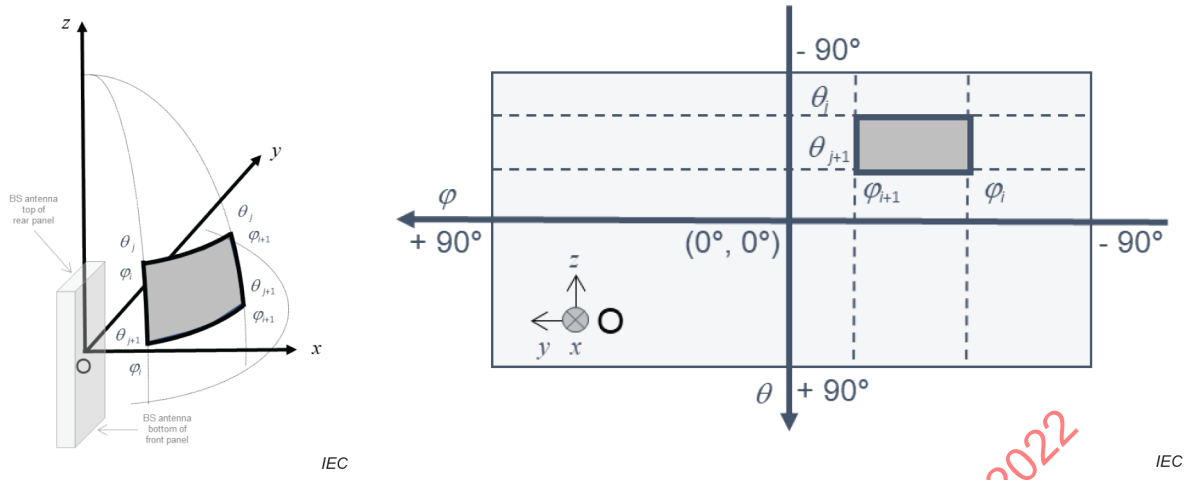
When implementing the compliance approaches specified in 6.2.3, actual transmitted power or EIRP monitoring is used to provide statistical analysis of the actual values and control P_{act} or $EIRP_{act}(\varphi,\theta)$ such that the threshold values specified in 8.4.3 are not exceeded during operation.

Mobile network management systems (NMS) provide counters at fixed counter reporting time intervals representing the performance and operation of the system. Such counters can be used to monitor P_{act} or $EIRP_{act}(\varphi,\theta)$ and to verify that the values are maintained below the actual maximum threshold(s). Such counters are generally based on the processing of the BS baseband system parameters. Examples of relevant counters are provided in B.9.5.

In the case of BS with beam steering, the time-averaged transmitted power or EIRP can be monitored per segment, i.e. identified by a range of angles in azimuth $\varphi_i \le \varphi \le \varphi_{i+1}$ and elevation $\theta_j \le \theta \le \theta_{j+1}$, see Figure 19. For each segment, the counter shall take into account all the relevant transmissions, including the main lobe and side-lobes of beams.

The duration of the monitoring period used to assess the CDF of the counters shall represent accurately the variability of operations, e.g. considering load variations within a day or a week or other seasonal effects in touristic areas, etc.

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a) 3D view

b) Mercator view from the BS antenna

Figure 19 – Example of segments used for monitoring and control of BS using mMIMO or beam steering

8.4.3 Actual transmitted power or EIRP control

When implementing the compliance approaches specified in 6.2.3, actual transmitted power or EIRP control is implemented such that the threshold value(s) configured for each cell or cell segment of the BS is not exceeded during operation.

Tools to control the actual transmitted power or EIRP include, but are not limited to, systems that limit the BS scheduled resources (e.g. LTE RB) so that the actual transmitted power or EIRP remains below the configured threshold(s), see for example [40].

The actual transmitted power or EIRP control function can be activated either on the total cell or per cell segment for BS with beam steering, see Figure 19.

Because of traffic variations during normal operation, P_{act} or $EIRP_{act}$ might be smaller than the set threshold without the need to affect the resource allocation (e.g. scheduling) decisions of the BS.

For a multi-band BS product, control of the transmitted power or EIRP on the total cell or per cell segment shall be done for each operating band. The threshold(s) of P_{act} or $EIRP_{act}$ can be assigned statically for each band or reallocated based on the distribution among the different bands during operation.

In the case of BS with beam steering, because of traffic variation and the spatial distribution of the served users, see e.g. [31], [32], [33], [34], $EIRP_{act}(\varphi,\theta)$ might be smaller than the set threshold without the need to affect the scheduling decisions of the BS.

Controlling the time-averaged transmitted power distribution in any direction might be impractical. Thresholds of the time-averaged transmitted power or EIRP might be configured per segment, i.e. using a range of angles in azimuth $\varphi_i \le \varphi \le \varphi_{i+1}$ and elevation $\theta_j \le \theta \le \theta_{j+1}$, see Figure 19. In this case, the upper bound for $EIRP_{act}(\varphi,\theta)$ within the segment is given by the product of the maximum antenna gain in the segment and the corresponding power threshold.

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8.5 Methods for the assessment of RF exposure to multiple sources

RF exposure assessment that considers multiple sources is required under the following circumstances:

a) when the BS emits RF fields on multiple carrier frequencies and/or on multiple frequency bands;

b) when evaluating RF fields from multiple sources including ambient sources, see B.4.2.6.

For such evaluation, the physical quantity representative of the RF exposure is the total exposure ratio (TER) as specified in Equation (9). In the context of this document, the physical quantities used for the ER_i are expressed in terms of the ratio of SAR, power density, E-field strength squared, or H-field strength squared to the corresponding exposure limit. The TER shall include contributions from all relevant sources including contributions from all the transmitters of the BS (for evaluation purposes specified in 6.1, 6.2 and 6.3) and ambient sources for evaluation purposes (6.2 and 6.3).

$$\mathrm{TER} = \sum_{i=1}^{N} \mathrm{ER}_i \tag{9}$$

where

ER_i is the exposure ratio for the source i;

N is the total number of sources considered in the assessment.

TER should be calculated for localized and whole-body exposure separately. The summation formulas are derived from the applicable regulation or exposure limits. Exposure to multiple sources is deemed to comply with the applicable exposure limits if the TER is less than or equal to 1. Equation (10), Equation (11) and Equation (12) provide examples based on international exposure guidelines.

For basic restrictions derived from ICNIRP-1998 [2], the $\mathrm{TER}_{\mathrm{BR}}$ is specified by Equation (10).

$$\mathrm{TER}_{\mathrm{BR}} = \sum_{i=100\ \mathrm{kHz}}^{10\ \mathrm{GHz}} \frac{\mathrm{SAR}_i}{\mathrm{SAR}_{\mathrm{L}}} + \sum_{j>10\ \mathrm{GHz}}^{300\ \mathrm{GHz}} \frac{S_j}{S_{\mathrm{L}}} \tag{10}$$

where

SAR_i is the SAR caused by exposure at frequency i;

$\mathrm{SAR}_{\mathrm{L}}$ is the SAR basic restriction;

S_j is the power density at frequency j;

S_{L} is the power density basic restriction.

The values of SARs and power densities in the above formula can be for the whole body or part of the body. Local SARs should be summed together; whole-body SARs should be summed together. Partial-body exposure levels should not be summed with whole-body exposure levels.

For basic restrictions derived from ICNIRP-2020 [1], the $\mathrm{TER}_{\mathrm{BR}}$ is specified by Equation (11).

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$$\mathrm{TER_{BR}} = \sum_{i=100\ \mathrm{kHz}}^{6\ \mathrm{GHz}} \frac{\mathrm{SAR}_i}{\mathrm{SAR_L}} \tag{11}$$

where

SAR_i is the SAR caused by exposure at frequency i;

$\mathrm{SAR_L}$ is the SAR basic restriction.

NOTE 1 ICNIRP-2020 introduced basic restrictions above 6 GHz based on absorbed power density for localized RF exposure and SAR for whole-body exposure. However, absorbed power density is not addressed in this document and whole-body SAR measurement techniques are specified only up to 6 GHz, see 8.1. Therefore, Equation (11) corresponds to the part of ICNIRP-2020 basic restriction summation formula that is applicable in this document for basic restrictions. Summation formulas up to 300 GHz are provided in this document based on evaluation of reference levels.

For reference levels derived from ICNIRP-2020 [1], the TER (for source region II and source region III) is defined by Equation (12). ICNIRP-1998 [2] has a very similar equation with a frequency split at 1 MHz instead of 30 MHz.

$$\mathrm{TER_{RL}} = \sum_{i=100\ \mathrm{kHz}}^{30\ \mathrm{MHz}} \max\left[\left(\frac{E_i}{E_{\mathrm{L},i}}\right)^2 ; \left(\frac{H_i}{H_{\mathrm{L},i}}\right)^2\right] + \sum_{j>30\ \mathrm{MHz}}^{300\ \mathrm{GHz}} \frac{S_j}{S_\mathrm{L}} \tag{12}$$

where

E_i is the electric field strength at frequency i;

$E_{\mathrm{L},i}$ is the electric field reference level at frequency i;

H_i is the magnetic field strength at frequency i;

$H_{\mathrm{L},i}$ is the magnetic field reference level at frequency i;

S_j is the power density at frequency j;

S_L is the power density reference level.

The values of RF field strength and power density in the above formula can be for the whole body or part of body. Partial-body quantities should be summed together; whole body quantities should be summed together. Partial body should not be summed with total body.

The TER can be derived from the summation of ER contributions obtained based on reference levels as well as basic restrictions.

Other examples of summation formulas are provided in IEC 62311.

NOTE 2 Correlated fields are rarely encountered from separate antennas on mobile communications. IEC TR 62630 [41] provides general information about summation principles for correlated or uncorrelated (in time) sources.

8.6 Methods for establishing the BS transmitted power or EIRP

The BS RF transmitted power or EIRP can be established:

a) by using manufacturer's data, in which case the uncertainty shall be assessed using the tolerance stated by the manufacturer; or

b) by direct measurement, in which case the uncertainty shall be the uncertainty of the measurement combined with the manufacturer's stated tolerance; or

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c) by using the actual maximum approach as specified in 6.2.3, 8.4 and Clause B.9.

When performing direct measurements, it is recommended to follow the procedures specified by international standardization bodies, such as 3GPP TS 38.141-1 [42] and 3GPP TS 38.141-2 [43] for NR, or standards required for product certification, such as EN 301 908 series, see [44], [45], [46], [47], [48]), so that the measured values are consistent with BS transmitted power or EIRP parameters used in manufacturer's data. Complementary information about the measurement methods and setups is provided in Clause B.10.

A lower value can be used if there is justification based on a detailed knowledge of the constraints on specific measurement system parameters.

9 Uncertainty

Uncertainty shall be estimated for every reported measured and calculated RF field strength, power density or SAR evaluation. It shall take into account specific requirements specified in Annex B for each evaluation method. Annex G provides general information and additional guidance on how to estimate uncertainty can be found in JCGM 100:2008 [49]. Although JCGM 100:2008 [49] is concerned with measurement uncertainty, the same concepts can be extended to computational uncertainty.

The expanded uncertainty for the evaluation should be below the target values specified for each method in 6.2.9, 6.3.6 and Annex B which represent industry best practice. It shall not exceed the maximum values specified in 6.2.9, 6.3.6 and Annex B. Under this condition, the evaluation result shall be compared directly to the exposure limit. However, the entity performing the uncertainty analysis also needs to be aware of the applicable regulations. See additional information and guidelines in Annex H.

Where there is a requirement for the assessment to be performed at maximum operating power or a set power level, variations due to product transmitted power or EIRP control should not be considered when evaluating the expanded uncertainty.

Where the extrapolation factor is known, additional uncertainty is not required, see Annex B and for information about RF power variations for different technologies see Annex E.

Where an extrapolation factor is unknown, additional uncertainty for scaling to maximum power shall be appropriately accounted for in the uncertainty evaluation.

The total combined uncertainty is based on a mathematical model which specifies how the influence quantities are added, see Clause G.3. A simple multiplicative model, expressed as a linear series of dB variation terms, is generally appropriate as provided in Table B.7 and Table B.8. Alternatively, the total combined uncertainty can be determined by combining uncertainties expressed in percent for SAR assessments. The use of mixed dB and linear units shall be avoided when determining the combined uncertainty.

The issue of conversion between linear and log units has been examined in [50] in addition to its effect on the uncertainty evaluation from a mathematical point of view. The approach used in [50] can be implemented to each particular case of uncertainty evaluation by using logarithmic expression. The chosen unit can affect the uncertainty evaluation results, and it can result in an overestimation or underestimation of the uncertainty.

10 Reporting

10.1 General requirements

The results of each evaluation or assessment carried out, and all information necessary for their interpretation, shall be reported accurately, clearly, unambiguously, and objectively.

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All the information needed for performing repeatable evaluations or assessment giving results within the required calibration and uncertainty limits shall be recorded. More detailed requirements are provided in Clause 6 for each evaluation type.

Further guidelines on the evaluation or assessment report can be found in ISO/IEC 17025 [51].

10.2 Report format

The format shall be designed to accommodate each type of evaluation or assessment performed whilst being as concise as is consistent with clarity. Depending on the applicable regulations, the report should indicate if it has been prepared by a laboratory under accreditation. Example reports are presented as case studies in IEC TR 62669 [5].

The report itself should consist of, but not be limited to, the following items:

a) a title;

b) the name and address of the laboratory or entity performing the evaluation or assessment, and the address where the measurements/computations were carried out, if different from the laboratory;

c) unique identification of the report (such as the serial number), and on each page an identification such that the page is recognized as a part of the test report, and a clear identification of the end of the test report;

d) the name and address of the client;

e) a description of the item(s) evaluated;

f) the date(s) of the evaluation;

g) the applicable standards and regulations;

h) the regions or locations at which the evaluation or assessment was performed;

i) where relevant, conditions that can influence evaluated data:

   1) for exterior or interior surveys, a description/photograph of the environment, illustrating the proximity of antennas to absorbing, scattering, or re-radiating structures located above, in front, or beneath the surface;

   2) weather conditions, and unusual or uncontrollable human movement in the survey area;

j) the evaluation methods employed (either explicitly described or by referencing the document describing the evaluation method);

k) the evaluation results with, where appropriate, the units of measurement – for example, for spectrum surveys, plots, or tabulations of RF field strength versus frequency;

l) measurement equipment and/or simulation software used:

   1) lists of measurement equipment and/or simulation software;

   2) measurement antenna/probe used (its height, orientation information, antenna factor/gain, type, and frequency range);

   3) cable attenuation between the measurement antenna/probe and associated equipment, unless it is included in the antenna factor/gain;

   4) all gains or losses of measurement system components – amplifiers, attenuators, power splitters, filters, etc.;

   5) any internal attenuator setting;

   6) frequency or frequencies being measured;

   7) bandwidth used for the evaluation;

   8) detector functions selected and characteristics – for example, time constants, channel decoding;

   9) post detector filter characteristics such as bandwidth;

   10) type of output – for example, log, linear, and characteristics (for example, range);

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11) signal and noise levels measured;

12) confirmation of traceable calibration;

m) the name(s), function(s) and signature(s) or equivalent identification of person(s) performing the evaluation and authorizing the evaluation report;

n) where relevant, a statement to the effect that the results relate only to the items tested;

o) where relevant, a statement to the effect that the evaluation takes into consideration the intended use or foreseeable use of the BS;

p) uncertainty analysis;

q) opinions and interpretations.

10.3 Opinions and interpretations

When opinions and interpretations are included, the report shall record the basis upon which these have been made. Opinions and interpretations shall be clearly marked as such in the evaluation or assessment report.

If opinions and interpretations are included in the report, it should consist of, but not be limited to, the following:

a) where appropriate, an opinion on the statement of compliance of the results with limit requirements;

b) fulfilment of contractual requirements;

c) recommendations on how to use the results;

d) guidance to be used for improvements.

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Annex A
(informative)

Source-environment plane and guidance on the evaluation method selection

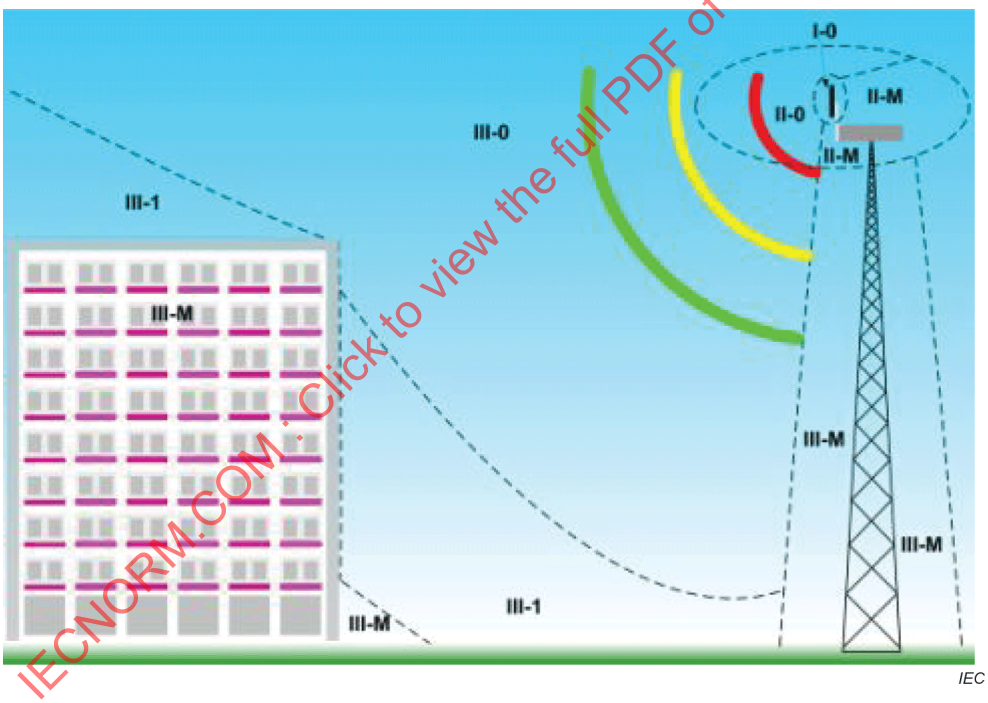
A.1 Guidance on the source-environment plane

A.1.1 General

Complementary information and examples are provided in A.1.2 and A.1.3 for different types of antennas and antenna installations in order to facilitate the understanding of the source-environment plane and of the source-region boundaries specified in Clause 7.

A.1.2 Source-environment plane example

An example of the application of the source-environment plane applied to a typical tower installation is depicted in Figure A.1. The elevation view of a BS antenna mounted on a tower or on a wall is shown.



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Figure A.1 – Example source-environment plane regions near a base station antenna on a tower

Depending on frequency and dimensions, the source regions progress from region I to III. In Figure A.1, the environment regions are classified as follows.

a) In the majority area of the main beam (coloured radials), where reflections are irrelevant, environment region 0 is applicable.

b) Outside the main beam, there is a single reflector (off the face of the building), therefore environment region 1 is applicable.

c) Along the rooftop, where a significant reflector (the roof-top itself) is located, environment region 1 is applicable.

d) The environment where the beam has penetrated the building and there are multiple reflectors from internal walls and other structures is designated environment region M.

e) The areas below and behind the antenna where the antenna is obscured (by the tower structure and/or headframe) and these elements reflect/reradiate RF fields are both designated environment region M.

In line-of-sight (LoS) to the antenna and above the antenna there is an area where roof-top reflections are not relevant and so environment region 0 applies.

Another example is shown in Figure A.2 for a roof-top installation.

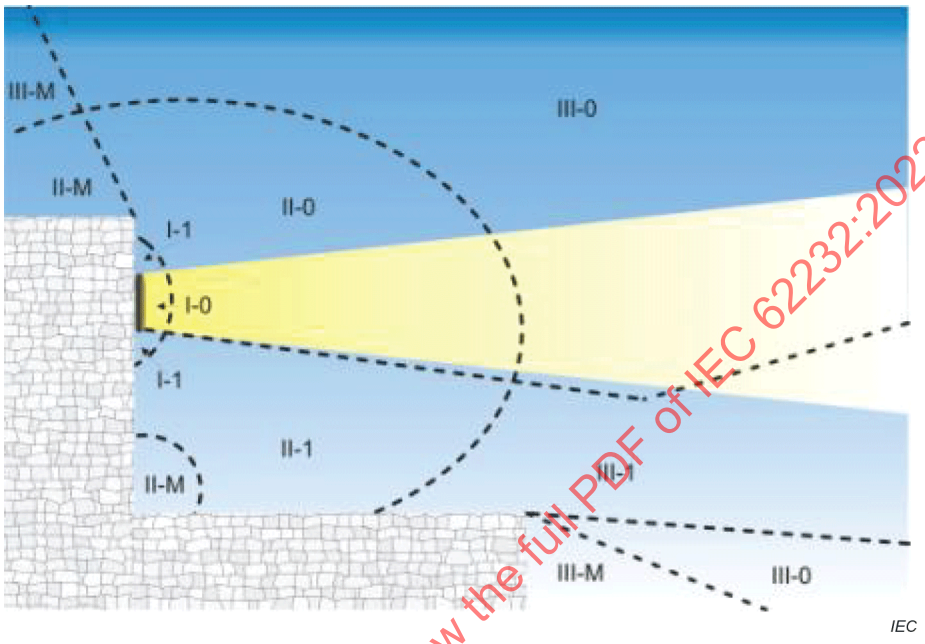


Figure A.2 – Example source-environment plane regions near a roof-top antenna that has a narrow vertical (elevation plane) beamwidth (not to scale)

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A.1.3 Source regions

A.1.3.1 General

The space surrounding an antenna is conventionally divided into two principal regions: one near the antenna called the near-field region and one at a larger distance called the far-field region. The near-field region is usually subdivided into the reactive and the radiating near-field regions. Typically, the far-field region is the region of the field of the antenna where the angular field distribution is essentially independent of the distance from a specified point in the antenna region. The reactive near-field region is the portion of the near-field region immediately surrounding the antenna, wherein the reactive field predominates [52].

Antenna field regions are often described in textbooks in terms of:

a) reactive/radiating near-field boundary. This can be described in a number of ways: where the reactive and radiating fields have the same magnitude is one approach, another is where the radiating fields dominate by a given amount;

b) far-field, which can be described based on how far from the antenna it is possible to accurately evaluate the directivity as would be observed from a long way away from the antenna.

A.1.3.2 Source definition and antenna geometry

Subclause A.1.3.2 describes the source regions which should be used. The antenna type, antenna geometry and evaluation point are all factors which influence the source region. Boundary definitions for intentionally radiating cables (also known as "leaky feeders"), reflectors and default source region are also presented.

Prior to categorizing the evaluation source regions, some fundamental antenna geometry variables need to be listed. Figure A.3 presents the geometry of an antenna configuration.

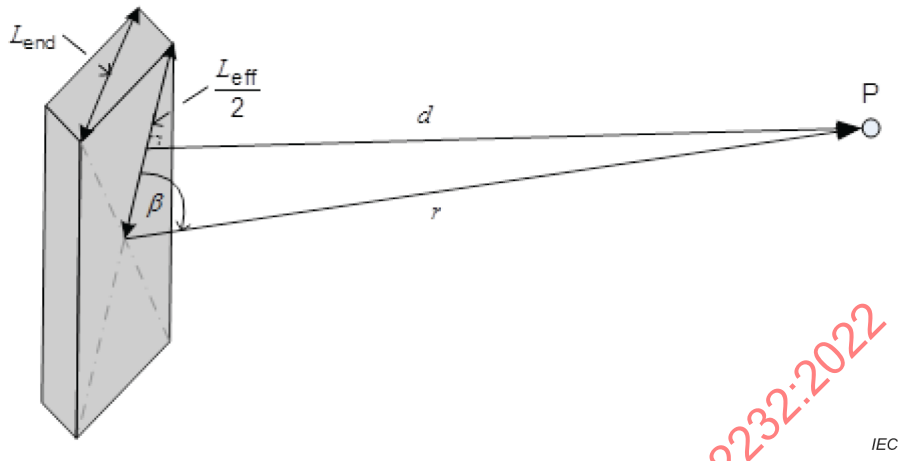


Figure A.3 – Geometry of an antenna with largest linear dimension L_{eff} and largest end dimension L_{end}

In Annex A, the following variables are used:

r is the distance from the centre point on the major axis of the antenna (the origin) to a point P, specifically:

r_{III} is the minimum distance from the antenna centre point to the boundary between source region II and source region III;

d is the minimum distance from the surface of the antenna to a point P, specifically:

d_I is the minimum distance from the surface of the antenna to the boundary between source region I and source region II;

d_{III} is the minimum distance from the surface of the antenna to the boundary between source region II and source region III;

d_{end} describes a surface in accordance with Table A.4 considering L_{end};

d_r describes a surface in accordance with Table A.4 considering L_{eff};

λ is the wavelength measured in metres;

β is the angle between the main axis (along the largest linear dimension) of the antenna and the line from the origin of the antenna to a point (e.g. on the source region II to source region III boundary);

L_{end} is the maximum end dimension measured in metres orthogonal to the front face (the chassis depth) of the antenna;

L_{eff} is the maximum dimension measured in metres between two points on the front face of the antenna.

Table A.1 specifies the source regions.

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Table A.1 – Definition of source regions

Source region I	**Source region II**	**Source region III**
$0 \le d < d_{\mathrm{I}}$	$d_{\mathrm{I}} \le d < d_{\mathrm{III}}$ **or** $d \ge d_{\mathrm{I}}$ and $r < r_{\mathrm{III}}$	$d_{\mathrm{III}} \le d < \infty$
In region I, reactive power components are consequential. The power density oscillates and, depending on the evaluation location, lower values might be obtained closer to the antenna in contrast to higher values further away	Radiating near-field region.	Far-field conditions. In Region III, the antenna pattern in the product documentation is applicable.
Where distances d_{I}, d_{III} and r_{III} are specified in Table A.2, Table A.3, Table A.4, Table A.5, in accordance with antenna classification: • Default source region boundaries – see Table A.2. • Antennas with maximum dimension less than 2,5 λ – see Table A.3. • Linear/planar antenna arrays of small elements aligned linearly, normally along a vertical axis, and with more elements on the vertical axis than horizontally and with the maximum dimension greater than 2,5 λ – see Table A.4. • Equiphase radiating apertures (e.g. parabolic dish antenna) with maximum dimension >> λ – see Table A.5. • Radiating cables – see Table A.6. NOTE Some evaluation methods described in this document specify additional constraints defining where the method can be employed. The evaluation zones can therefore differ from the source regions.		

The default source region boundaries, see Table A.2, should be used when there is any doubt as to the classification of the source antenna. For common antenna classifications (antennas and radiating cables), Table A.3, Table A.4, Table A.5, and Table A.6 provide examples of source region boundaries.

NOTE Where similar regions are specified in Annex B, the definitions in Annex B apply.

Table A.2 – Default source region boundaries

Source region I to source region II boundary[a]	**Source region II to source region III boundary[a]**
$d_{\mathrm{I}} = \max\left(\frac{\lambda}{2\pi},\ L_{\mathrm{eff}},\ \frac{{L_{\mathrm{eff}}}^2}{4\times\lambda}\right)$	$d_{\mathrm{III}} = \max\left(5\times\lambda,\ 5\times L_{\mathrm{eff}},\ \frac{0{,}6\times {L_{\mathrm{eff}}}^2}{\lambda}\right)$
NOTE The distance limits of the default source regions are smaller than those proposed in textbooks covering exact descriptions of antennas. The textbook distance limits were reduced based on not noticeably influencing the uncertainty of the RF field strength evaluation [37].	
[a] These distance limits of the regions are applicable generally. Antennas exist for which these limits are conservative, for example for source region I, $\lambda/2\pi$ or less is applicable even if L_{eff} or $L_{\mathrm{eff}}^2/(4\times\lambda)$ are larger. However, unless these cases are included in Annex A, sustainable proof is required.	

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Table A.3 – Source region boundaries for antennas with maximum dimension less than 2,5 λ

Source region I to source region II boundary[a]	Source region II to source region III boundary
$d_{\mathrm{I}} = \lambda / 2\pi$	In [53], the source region II to source region III boundary surface is a sphere radius r_{III}, centred at the middle of the antenna: $r_{\mathrm{III}} = \begin{cases} 1{,}6 \times \lambda & \text{for } L_{\mathrm{eff}} < 0{,}3 \times \lambda \\ 5 \times L_{\mathrm{eff}} & \text{for } 0{,}3 \times \lambda \le L_{\mathrm{eff}} < 2{,}5 \times \lambda \end{cases}$

[a] Measurements of either E or H are acceptable at distances down to $\lambda/2\pi$ from the surface of the antenna by considering (a) the increase in uncertainty, see A.1.3.3.1, and (b) that lower power density values can be obtained closer to the antenna in contrast to higher values further away.

Table A.4 – Source region boundaries for linear/planar antenna arrays with a maximum dimension greater than or equal to 2,5 λ

Source region I to source region II boundary[a]	Source region II to source region III boundary
$d_{\mathrm{I}} = \lambda / 2\pi$	The source region II to source region III boundary is specified by an examination of two surfaces surrounding the antenna evaluated from functions of L_{eff} and L_{end}: A large surface described by r, centred on the middle of the antenna: $r = \frac{2 \times L_{\mathrm{eff}}^2}{\lambda} \sin^2 \beta + \frac{L_{\mathrm{eff}}}{2} \lvert\cos \beta\rvert - \frac{\lambda}{32}$ from which the corresponding distance, d_{r} to the surface of the antenna can be determined: $d_{\mathrm{r}} = r \lvert\sin\beta\rvert$ A smaller surface described by d_{end}, considering the end dimensions of the antenna: $d_{\mathrm{end}} = \begin{cases} 1{,}6 \times \lambda & L_{\mathrm{end}} < 0{,}3 \times \lambda \\ 5 \times L_{\mathrm{end}} & 0{,}3 \times \lambda \le L_{\mathrm{end}} < 2{,}5 \times \lambda \\ \frac{2 \times L_{\mathrm{end}}^2}{\lambda} & L_{\mathrm{end}} \ge 2{,}5 \times \lambda \end{cases}$ $d_{\mathrm{III}} = \max \begin{pmatrix} d_{\mathrm{r}} \\ d_{\mathrm{end}} \end{pmatrix}$

[a] Measurements of either E or H are acceptable at distances down to $\lambda/2\pi$ from the surface of the antenna by considering (a) the increase in uncertainty, see A.1.3.3.1, and (b) that lower power density values can be obtained closer to the antenna in contrast to higher values further away.

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Table A.5 – Source region boundaries for equiphase radiation aperture (e.g. dish) antennas with maximum reflector dimension much greater than a wavelength

Source region I to source region II boundary	Source region II to source region III boundary
Within the main beam before the first null is reached: $d_{\mathrm{I}} = \frac{L_{\mathrm{eff}}^{\ 2}}{4 \times \lambda}$ Outside the main beam and after the first null is reached[a]: $d_{\mathrm{I}} = \max\left(\begin{matrix}\lambda/2\pi \\ L_{\mathrm{eff}}\end{matrix}\right)$	$d_{\mathrm{III}} = \frac{0{,}6\ L_{\mathrm{eff}}^{\ 2}}{\lambda}$
[a] Outside the main beam and after the first null is reached, measurements of either E or H are acceptable at distances down to $\lambda/2\pi$ from the surface of the antenna by considering (a) the increase in uncertainty, see A.1.3.3.1, and (b) that lower power density values can be obtained closer to the antenna in contrast to higher values further away.	

Table A.6 – Source region boundaries for radiating cables

Source region I to source region II boundary	Source region II to source region III boundary
$d_{\mathrm{I}} = \lambda / 2\pi$	d_{III} is not usefully definable since radiating cable lengths are typically tens to hundreds of metres, thus much greater than the evaluation point distance from the radiating structure
NOTE Radiating cables are also known as leaky feeders.	

A.1.3.3 Boundary between source regions for BS antennas with small elements, e.g. dipoles/slots/loops

A.1.3.3.1 Boundary between source region I and source region II

Various criteria can be used for determining the source region boundaries for BS antennas with small elements. The boundary between source regions I and II is directly related to the influence of the reactive near-field. In turn, the reactive near-field region is a function of the antenna geometry.

Considering the region within which the maximum RF field strength can be found, λ is the appropriate value for d_{I}.

Considering the requirement to measure both electric field strength and magnetic field strength (or SAR), the following apply.

a) For dipole type antennas, prevalent in many BS antenna designs, an analysis was performed in IEC 62311 based on the analytical expressions for fields radiated by a short linear element. By calculating the ratio of the total power density to the radiated power density for a few simple array antennas, as well as for a single dipole element, it was found that the effective maximum difference between the total and the radiated power density would be 10 %, 0,4 dB, or less for distances larger than a quarter of a wavelength.

b) In [54], [55] the measurement error is stated to be less than 1 dB for a distance of $\lambda/4$.

c) In [56], both local SAR and whole-body SAR are given as a function of distance for a number of scenarios with different RBS antennas showing the gradual transition between different field regions.

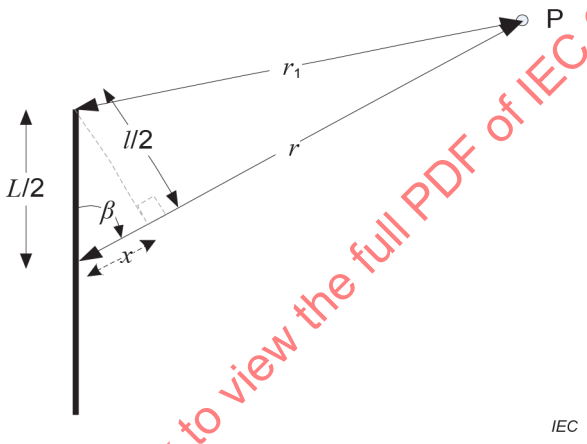
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Provided the increased uncertainty is considered, measurement of either electric field strength or magnetic field strength at distances larger than or equal to $\lambda/4$ from the surface of the antenna is acceptable.

A.1.3.3.2 Boundary between source region II and source region III for maximum antenna dimension $L \geq 2{,}5\ \lambda$ and elements in a linear configuration

The criteria for determining the source region II and III boundaries for BS antennas with small elements is discussed here. Far-field conditions can be said to apply when the maximum phase error (phase difference between fields emanating from the centre and the edge of the antenna) is smaller than $\pi/8$ [57]. Translated to distance this corresponds to a path difference of $\lambda/16$ between the observation point and the current sources in the extremities of the antenna array.

Consider the general configuration of Figure A.4 with an antenna of length L and an evaluation at point P. The path length represented by x is constant for all $r > x$ and helps describe the far-field directivity. The $\lambda/16$ constraint therefore applies to the difference in path lengths between paths r-x and r_1.



Key

L antenna array total length

l array projected length at observation point P

Figure A.4 – Maximum path difference for an antenna with largest linear dimension L

From geometry and [58], Equation (A.1) is obtained.

$$x = \frac{L}{2}\left|\cos\beta\right| \quad \text{and} \quad r_1^2 = r^2 + \frac{L}{4}^2 - r \cdot L\left|\cos\beta\right| \tag{A.1}$$

For constraint $r_1 - (r\text{-}x) = \lambda/16$, leads to Equation (A.2):

$$r = \frac{2 \times L^2}{\lambda}\sin^2\beta - \frac{\lambda}{32} + \frac{L}{2}\left|\cos\beta\right| \tag{A.2}$$

For the special case of $\beta = 90°$(main beam), and ignoring the term $\lambda/32$, this simplifies to the often quoted $r = 2 \times L^2 / \lambda$. However, note that for other values of β, Equation (A.1) and Equation (A.2) give smaller far-field distances, e.g. see Table A.7.

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Table A.7 – Far-field distance r measured in metres as a function of angle β

β	10°	30°	60°	90°	120°	150°	170°
r	1,8 m	7,5 m	20,5 m	26,7 m	20,5 m	7,5 m	1,8 m
NOTE This is for the case where L = 2 m and λ = 0,3 m (i.e. 1 GHz).							

A.1.3.4 Source regions for equiphase radiating aperture (e.g. parabolic dish) antennas

A.1.3.4 describes the criteria for determining the source region boundaries for equiphase radiating apertures. This class of antennas includes parabolic dish antennas where, when observed in the main beam, a significant cross-sectional area of reflector is reflecting the radiated energy from the feed source into a narrow beam.

Within the main beam, apply the criteria when the oscillation of the power density stops for increasing distance as shown by ETSI TR 102 457 [59], and as used in FCC OET Bulletin 65 [37]. Additional discussion is provided in [60].

Outside the main beam and after the first null is reached, the "equiphase" conditions do not apply and so the source regions can be based on Table A.2.

A.2 Select between computation or measurement approaches

Table A.8 provides guidance on selecting between computation and measurement methodologies based on a number of practical considerations.

If measurement is selected, then the next step is Clause A.3. Otherwise, if computation is selected then the next step is Clause A.4.

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Table A.8 – Guidance on selecting between computation and measurement approaches

Computation (B.3.1, Clause B.6 and Clause B.7)	versus	Measurements (B.3.2, Clause B.4 and Clause B.5)
Unable to access area to be evaluated. For example, due to safety considerations or due to not having right of access by building / land owner.	←	
	→	Insufficient information available to perform computation.
Requirement is to present a comprehensive field visualization.	←	
	→	Requirement is to cover specific limited routes/locations e.g. access route, nominated locations.
	→	Client requires measurement.
Client requires computation.	←	
Requirement includes an evaluation in locations where, or at times when, the BS is not radiating (e.g. prior to construction).	←	
	→	Requirement is for a physical demonstration to interested people.
NOTE The arrow presents which column is suggested considering the applicability of the cases described in the cells.		

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A.3 Select measurement method

A.3.1 Selection stages

Determine the measurement method in the following stages:

a) determine if SAR, RF field strength or power density measurement is appropriate, see A.3.2;

b) select either broadband or frequency selective measurement approach, see A.3.3;

c) determine which measurement procedures are applicable, see A.3.4.

A.3.2 Selecting between RF field strength, power density and SAR measurement approaches

For any in-situ measurement, and in environment regions *-1 and *-M (* means I or II or III, see 7.2.2.2), RF field strength and power density measurement are applicable within their applicable frequency range.

For laboratory measurements in source-environment plane regions I-0 and II-0, see 7.2.2.2, either RF field strength or power density, see Clause B.4 or SAR measurement, see Clause B.5 can be selected. Within the applicable frequency range SAR measurement is recommended for region I-0 and where the key consideration is in obtaining the most accurate results for example, to determine the smallest volume that needs to be enclosed within a compliance boundary. RF field strength or power density measurement can be selected where it is simpler to implement or at those frequencies for which SAR is not applicable.

NOTE 1 Generally, the spatial-peak RF field strength relates closely to the local SAR [61].

NOTE 2 Some international exposure standards prevent the utilization of reference levels at some frequencies when in very close proximity to the source (e.g. within $\lambda/2\pi$)

A.3.3 Selecting between broadband and frequency selective measurement

Determine if broadband or frequency selective measurement is appropriate in accordance with Table A.9.

Table A.9 – Guidance on selecting between broadband and frequency selective measurement

Broadband (see B.4.2.3)	**versus**	**Frequency selective** (see B.4.2.4)
Indication of total field: A broadband measurement can provide a simple means to indicate the total field and requires care that in certain circumstances the results are correctly interpreted and presented: • no frequency discrimination required; • precise knowledge/control of evaluation parameters; • as indicative evaluation – for example, an initial scan to find the peak field using a broadband probe can be followed by a more detailed measurement using a frequency selective equipment.	⟷	Indication of total field: Frequency selective measurement is required when frequency discrimination is required, for example: • to evaluate constant part of transmitted signal for extrapolation, see Clause B.8; • to evaluate frequency weighting for exposure ratio.
Comparison with a limit: Where the RF field strengths are significantly below the applicable RF exposure limit. Where the BS is the single dominant source and either as an "as observed" evaluation without extrapolation is required; or, the output power of the BS is controlled during the measurement.	⟷	Comparison with a limit: Identifying and evaluating single and multi-frequency signals for comparison with a limit. Where extrapolation is required from a constant level part of the signal in the presence of other signals.
	→	Limit exceedance: In case of any doubt, or when the purpose is to confirm that a limit has been exceeded, the frequency selective method is recommended.
	→	Signal discrimination: A frequency selective method is essential for evaluating individual frequency bands or signal types. This includes identifying ambient fields for either inclusion or exclusion from final processing and reporting of results.
	→	Low level fields: Identifying and measuring signals in low RF field strength environments (e.g. public areas).
NOTE 1 The term "frequency selective" is used rather than "narrow band" to imply the ability to discriminate between frequencies. The term "broadband" is used when a wide spectrum range is measured simultaneously without frequency discrimination. Measurement equipment which can indicate the RF field strength from a logical channel (e.g. using a channel decoder) is also deemed to be "frequency selective". NOTE 2 The arrow presents which column is suggested considering the applicability of the cases described in the cells.		

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A.3.4 Selecting RF field strength measurement procedures

Select appropriate measurement procedures in accordance with Table A.10.

Table A.10 – Guidance on selecting RF field strength measurement procedures

Measurement procedure	Guidance on selection
Handheld – Fixed evaluation location (see B.4.2.5.1)	Convenient and time efficient method to identify fields at specific evaluation locations of interest.
Handheld – Sweeping a surface to identify the PoI (see 6.3.4) or a volume to determine a RF field strength or power density value of interest and/or its location (see B.4.2.5.2)	Convenient and time efficient method to identify location where a specific RF field strength level is observed. For example, this procedure is useful for establishing a control boundary. Convenient and time efficient method to identify spatial-peak RF field strength in a volume. For example, this procedure is useful in public areas to demonstrate low RF field strengths, or to establish locations where more precise evaluation is required when comparing with a limit value.
Tripod – (see B.4.2.5.3)	Where one or more of the following are important: • measurements at fixed or nominated points in space are required; • monitoring of fields over long time periods; • minimizing influence of body during measurement.
Automated scanning – (see B.4.3.3.2.1)	Where the RF field strength is being evaluated in laboratory conditions.
Spatial averaging – (see 6.4.1 and B.3.3)	Where a spatially-averaged value is required. For example, for comparison with the exposure limits or to establish a representative average RF field strength over the area of a human body in complex field conditions (environment regions 1 and M).
Time averaging – (see 6.4.2 and B.3.4)	To establish time-averaged RF field strength. For example, for information purposes, or to establish value for more representative comparison with limit value specified as an average over time or to determine the actual maximum RF field strength.

A.4 Select computation method

Select appropriate computation procedures in accordance with Table A.11.

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Table A.11 – Guidance on selecting computation methods

<table>
<tr><th>Basic computation methods
(see B.3.1 and Clause B.6)</th><th>versus</th><th>Advanced computation methods
(see Clause B.7)</th></tr>
<tr><td>Where the main requirement is simplicity of evaluation.
Minimal source or environment information required/available.</td><td>↔</td><td>Where the main requirement is to obtain the most accurate results for example to determine the smallest volume that needs to be enclosed within a compliance boundary.
Where the required source and environment information is available.</td></tr>
<tr><td>↓</td><td></td><td>↓</td></tr>
<tr><td>Basic – Cylindrical-spherical formulas
Simple field – better suited to source regions II and III.
Select the cylindrical-spherical formulas for a quick and simple power density evaluation.
The calculations are easy to perform without the complexity/expense of advanced calculations, but at the expense of accuracy, i.e. the simple cylindrical-spherical formulas usually result in quick but over-conservative power density evaluations.</td><td></td><td>Advanced – Synthetic model and ray tracing
Advanced field – Well suited for accurate power density evaluations in source regions II and III.
The algorithm is relatively easy to implement and verify, alternatively, commercial software packages exist. When an implementation / software package is available, this method can be very powerful in producing quick, accurate and visually informative power density evaluations for simple or complex BS sites.</td></tr>
<tr><td>Basic – SAR estimation formulas
Simple SAR – better suited to source regions I and II.
Select the SAR estimation method for quick and simple SAR evaluation. The SAR estimation method is faster than the more advanced methods at the price of being somewhat more conservative.
When it comes to establishing compliance boundaries, the method is probably producing boundaries enclosing a smaller volume compared with techniques based on power density evaluations.</td><td></td><td>Advanced – Full wave RF field strength
Advanced field – Well suited for very accurate power density evaluations in source regions I and II.
Very complex and time consuming to implement and verify these algorithms, but a good number of commercial software packages are available. Even with these software packages available, the user should be proficient with the use of such packages and the time in setting up and verifying accurate antenna models should not be underestimated. However, the power density results obtained with such an evaluation are very accurate in both source regions I and II.</td></tr>
<tr><td></td><td></td><td>Advanced – Full wave SAR
Advanced SAR – Well suited for very accurate SAR evaluations in source regions I and II.
Very complex and time consuming to implement and verify these algorithms but a good number of commercial software packages are available.
Even with these software packages available, the user should be proficient with the use of such packages and the time in setting up and verifying accurate antenna AND human phantom models should not be underestimated. However, the obtained SAR results are the most accurate and authoritative evaluation possible for source regions I and II.</td></tr>
<tr><td colspan="3">NOTE The twin-headed arrow presents which column is suggested based on the most applicable cell description. Having determined basic or advanced approach, the relevant advanced/basic down arrow indicates the set of methods described in this document. The description that best matches the specific task required guides the selection of the specific method.</td></tr>
</table>

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A.5 Additional considerations

A.5.1 Simplicity

In general, the simplest evaluation method which satisfies the evaluation purpose should be selected. For example, a simple peak RF field strength evaluation, which is conservative, can be used with care to demonstrate compliance.

NOTE Compared to simple evaluations, more complex evaluations are likely to be able to assess compliance with an applicable exposure limit closer to the BS antenna. For example, a SAR evaluation might confirm the smallest volumes around an antenna wherein limits can be exceeded.

A.5.2 Evaluation method ranking

Where the results of one evaluation are being compared with a second evaluation, the highest-ranking evaluation method should take precedence; subject to both being applicable for the specific evaluation purpose and conditions. The highest-ranking evaluation method with valid applicability is the reference method for that exposure metric. Table A.12 ranks the evaluation methods included in this document.

Table A.12 – Guidance on specific evaluation method ranking

Evaluation exposure metric (see 7.2.3)	Evaluation method ranking (1 is highest-rank)				
	1	2	3	4	5
SAR (whole-body and localized)	Measurement (localized)	Full wave	SAR estimation formulas		
Power density; electric field strength; magnetic field strength	Frequency selective measurement	Broadband measurement[a]	Full wave	Ray tracing	Spherical / cylindrical formulas

[a] Under very limited evaluation conditions where all relevant information is known to enable accurate interpretation/extrapolation, see Clause B.8, broadband measurements are suitable. Otherwise, broadband measurements can result in a systematic overestimation of the RF field strength and are ranked 6.

A.5.3 Applying multiple methods for RF exposure evaluation

More than one evaluation method can be used to evaluate RF exposure near a BS antenna. The methods can be employed sequentially or concurrently provided there is a demonstration that the applicable exposure limit value is not exceeded, see Annex H. The applicable evaluation method providing the smallest compliance boundary around the antenna can be selected.

NOTE For example, a SAR measurement around a micro cell antenna or a SAR modelling around a larger base station antenna is likely to provide the smallest compliance boundary.

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Annex B
(normative)

Evaluation methods

B.1 Overview

Annex B specifies the evaluation methods that shall be used to measure or compute RF field strength, power density or SAR as required in Clause 6, Clause 7 and Clause 8. Each method description includes the applicability constraints within which it shall be employed, the information required to implement the method and how to characterize the uncertainty of the evaluation.

B.2 General

B.2.1 Coordinate systems and reference points

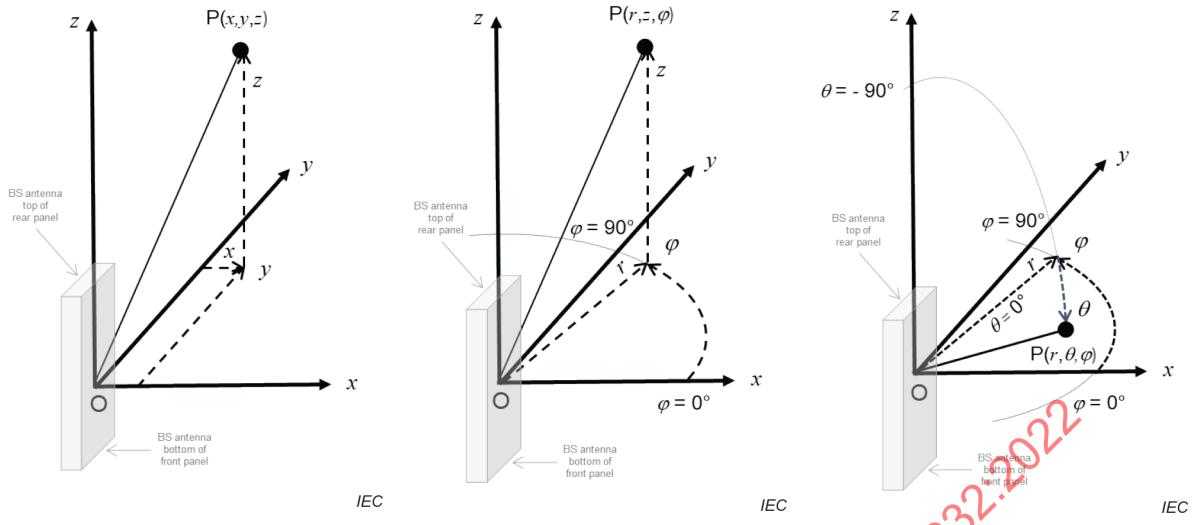
In theory, the reference point or origin "O" of the coordinate system corresponds to the BS antenna phase centre and coincides with the centre of an antenna's far-field radiation sphere. For practical reasons, where there is a clearly identified BS antenna (e.g. desktop unit with external antenna or where the BS antenna has exposed radiating elements), the reference point or origin "O" of the coordinate system shall be either the centre of the back or the front surface in case of panel antennas, the centre of the antenna in case of omnidirectional antennas or any characteristic point (e.g. bottom of the radome). For BS with built in antennas (e.g. desktop box with internal antenna) where there is no external indication of antenna position, the reference point shall be on the surface of the enclosure.

The assessment report shall include a description of the BS reference point, see 6.1.7, 6.2.10 and 6.3.7.

In accordance with the evaluation method, coordinates for BS antennas can be described in Cartesian, cylindrical or spherical coordinate systems in accordance with Figure B.1. For the common case of panel antennas, the back or front antenna panel coincides with the (yOz) plane, with the z-axis being directed up in the vertical direction. The (xOy) plane is the horizontal plane cutting the antenna panel in the middle with x-axis normal to the antenna front surface. Therefore, in the absence of beam tilting, the boresight of the antenna coincides with the (Ox) direction and the spherical coordinates φ = 0 (azimuth) and θ = 0 (elevation).

NOTE This spherical coordinate system is harmonized with common practice adopted by network operators, BS manufacturers and antenna manufacturers, see for example [62].

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a) Cartesian: P(x, y, z) **b) Cylindrical: P(r, z, φ)** **c) Spherical: P(r, θ, φ)**

Figure B.1 – Cartesian, cylindrical and spherical coordinate systems relative to the BS antenna (view from the rear panel)

B.2.2 Variables

Table B.1 specifies the dimension variables. Table B.2 specifies the variables relating to the RF power. Table B.3 describes the antenna variables that can be obtained from manufacturer's documentation. If N_e is not available, it can be determined from the antenna size and wavelength in accordance with B.6.3.5. Table B.4 describes the exposure metric variables.

Table B.1 – Dimension variables

Variable	Default Unit	Description
d_{xx}	m	Distance between points identified by the subscript xx
r_{xx}	m	Radius from point of origin, where subscript xx is used to identify the end point.
L_{xx}	m	Dimension of an antenna, phantom, measurement area or other object, where subscript xx is used to describe the specific case.
CD	m	Compliance distance

Table B.2 – RF power variables

Variable	Unit	Description	Notes
P or P_{avg}	W	Time-averaged transmitted power, see 3.17	P is also commonly expressed in dBm. For simplicity, P can be used in the text or formulas instead of P_{avg} provided this is clear and consistent with the method and purpose of the assessment.
$EIRP_{\varphi,\theta}$	W	equivalent isotropic radiated power, see 3.39	This is product of the input power P and the antenna gain $G_{\varphi,\theta}$ in direction specified in spherical coordinates at the frequency under evaluation. $EIRP_{\varphi,\theta}$ is also commonly expressed in dBm.

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Table B.3 – Antenna variables

Variable	Unit	Description
D	Linear ratio	Peak directivity of the antenna at the frequency under evaluation.
$D_{\varphi,\theta}$	Linear ratio	Directivity of antenna in direction specified in spherical coordinates at the frequency under evaluation.
G	Linear ratio	Peak antenna gain at the frequency under evaluation.
$G_{\varphi,\theta}$	Linear ratio	Antenna gain in direction specified in spherical coordinates at the frequency under evaluation.
$G_{\text{side lobe}}$	Linear ratio	Gain of the maximum side lobe in the vertical gain pattern at the frequency under evaluation.
$\Delta\varphi_{3\text{dB}}$	Radians	Azimuth HPBW at the frequency under evaluation.
$\Delta\theta_{3\text{dB}}$	Radians	Vertical HPBW at the frequency under evaluation.
γ	Radians	Electrical downtilt angle of the antenna main beam from x-y plane at the frequency of evaluation. Down is positive and up is negative.
N_{e}	Integer number	The number of antenna elements at the frequency of evaluation.

Table B.4 – Exposure metric variables

Variable	Unit	Description	Notes
S	W m^{-2}	Plane wave equivalent power density value over the longer period of either the modulation or the pulse waveforms	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}
$\overline{S}$	W m^{-2}	Spatially-averaged plane wave equivalent power density	Spatial averaging defined by spatial averaging scheme
E	V m^{-1}	RMS electric field strength over the longer period of either the modulation or the pulse waveforms	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}
$\overline{E}$	V m^{-1}	Spatially-averaged RMS electric field strength	Spatial averaging defined by spatial averaging scheme
H	A m^{-1}	RMS magnetic field strength over the longer period of either the modulation or the pulse waveforms	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}
$\overline{H}$	A m^{-1}	Spatially-averaged RMS magnetic field strength	Spatial averaging defined by spatial averaging scheme
SAR_{wb}	W kg^{-1}	Specific absorption rate averaged over the whole-body	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}
$\text{SAR}_{10\text{g}}$	W kg^{-1}	Peak spatial-average specific absorption rate in 10 g	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}
$\text{SAR}_{1\text{g}}$	W kg^{-1}	Peak spatial-average specific absorption rate in 1 g	Time averaging to address modulation and pulses or to be consistent with relevant P or P_{avg}

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B.3 RF exposure evaluation principles

B.3.1 Simple calculation of RF field strength and power density

B.3.1.1 Mast mounted BS

A typical RF exposure assessment case is shown in Figure B.2.

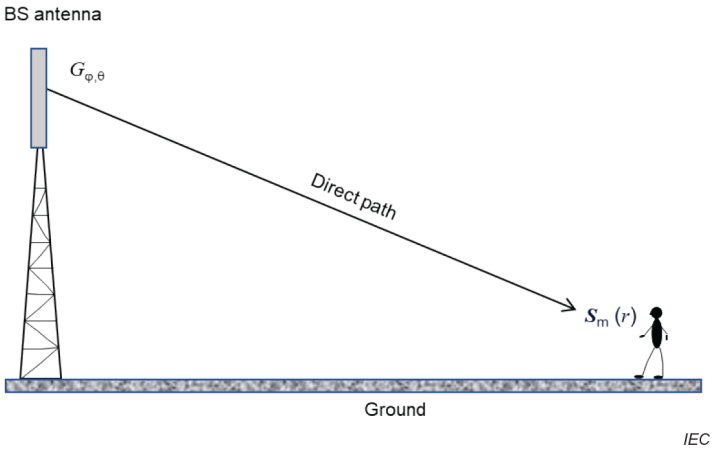


Figure B.2 – Typical RF exposure assessment case

As a first estimate, the spatially-averaged and spatial-peak equivalent power densities can be evaluated using the simple spherical formulas described in Equation (B.1) or Equation (B.2). Variables specified in B.2.2 are used.

$$S = \frac{P \cdot G_{\varphi,\theta}}{4\pi \cdot r^2} \tag{B.1}$$

$$S = \frac{\mathrm{EIRP}_{\varphi,\theta}}{4\pi \cdot r^2} \tag{B.2}$$

The associated RMS electric field strength E and magnetic field strength H can be evaluated using Equation (B.3) and Equation (B.4):

$$S = \frac{E^2}{120\pi} \approx \frac{E^2}{377} \text{ and } H = \frac{E}{\eta_0} \tag{B.3}$$

$$E = \frac{\sqrt{30 \times P \cdot G_{\varphi,\theta}}}{r} \tag{B.4}$$

The resulting distance of the compliance distance (CD) in this direction can be evaluated using Equation (B.5) or Equation (B.6).

$$\mathrm{CD} = \sqrt{\frac{P \cdot G_{\varphi,\theta}}{4\pi \cdot S_{\mathrm{lim}}}} \text{ or } \mathrm{CD} = \sqrt{\frac{\mathrm{EIRP}_{\varphi,\theta}}{4\pi \cdot S_{\mathrm{lim}}}} \tag{B.5}$$

$$\mathrm{CD} = \frac{\sqrt{30 \times P \cdot G_{\varphi,\theta}}}{E_{\mathrm{lim}}} \text{ or } \mathrm{CD} = \frac{\sqrt{30 \times \mathrm{EIRP}_{\varphi,\theta}}}{E_{\mathrm{lim}}} \tag{B.6}$$

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Main assumptions for using Equation (B.1) through Equation (B.6):

a) Domain of application: source regions II and III.

b) When applied in region II it might lead to an overestimate of RF exposure.

c) For the estimate of S, E or H to be conservative, P and $G_{\varphi,\theta}$ values shall be the upper bounds of the uncertainty.

d) Reflecting surfaces/objects, a ground plane and mounting structures are not allowed in the general direction of the evaluation point if Equation (B.4) through Equation (B.7) are to be used.

B.3.1.2 Impact of reflective ground plane

If a reflecting ground plane is present and is likely to impact RF exposure (e.g. see Figure B.3), the classical spherical formula in Equation (B.7) can be used:

$$S = (1+|\Gamma|)^2 \cdot \frac{P \cdot G_{\varphi,\theta}}{4\pi \cdot r^2} \tag{B.7}$$

where $|\Gamma|$ is the reflection coefficient of the reflector, e.g. ground plane, and other variables are specified in B.2.2.

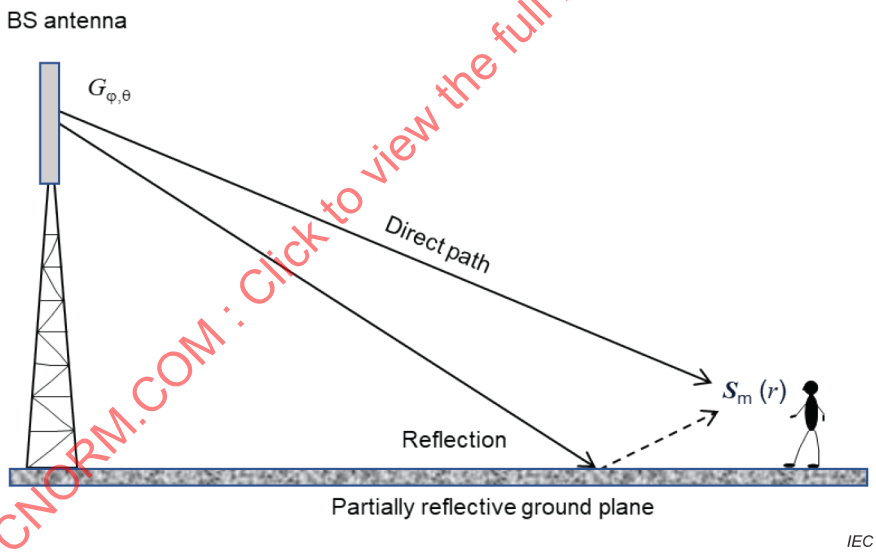


Figure B.3 – Reflection due to the presence of a ground plane

If the reflection coefficient $|\Gamma|$ is known, it can be used in Equation (B.7). Otherwise, the following reflection coefficient values can be used:

a) $|\Gamma| = 1$ for the theoretical highest RF field strength scenario of a perfectly conducting ground plane (e.g. flat metallic roof); or

b) $|\Gamma| = 0{,}6$ for typical [37] ground reflection conditions.

NOTE Propagation conditions other than ground reflection can also be considered in the evaluation of power density, see [63] and [64].

The exposure evaluation report shall report values and methodology used to determine the reflection coefficient.

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B.3.1.3 Simple calculations with massive MIMO antennas

The simple and classical spherical formulas can be used for compliance evaluation of massive MIMO and beamforming antennas, see for example [65]. In this case, the radiation pattern envelope $G_{\varphi,\theta}$ can be used in Equation (B.1), Equation (B.2), and Equation (B.4) through Equation (B.7).

As described in [66], if only the peak antenna gain G_p is known, an overestimation of the radiation pattern envelope for massive MIMO antennas can be calculated using Equation (B.8) assuming the boresight direction is φ = 0 and θ = 0, see B.2.1. Within the beam-steering range:

$$G_{\varphi,\theta} = G_p \cdot \cos\varphi \cdot \cos\theta \tag{B.8}$$

Outside the beam-steering range, using a flat value corresponding to the minimum gain within the beam-steering range provides a conservative estimate.

NOTE 1 The simple and classical spherical formulas provide a value of S representing the best estimate confidence level for the "technique uncertainty". The upper 95 % confidence level is +3,5 dB on the S determined by the simplified equation in [67] that fully describes the method to determine the three-dimensional gain pattern and the associated uncertainties used for the range of antennas evaluated in the reported study.

NOTE 2 Application of the classical spherical formula is also possible in source region II but can result in an overestimation of the spatially-averaged power density $\overline{S}$ and spatial-peak power density S.

B.3.1.4 BS installed underground

As a special case, when a base station installed underground forms a service area on the ground (see, for example, Figure B.4), use also Equation (B.7). In this case, reflection coefficient $|\Gamma|$ is generally larger than in the case of Figure B.3, because multiple reflections due to the presence of internal walls of the housing and surrounding asphalts and soils configuring the base station can be assumed. The reflection coefficient in this case can be obtained by comparing the calculated value obtained using Equation (B.7) with the measured value of the actual base station or the detailed computation values using full wave RF exposure computation B.7.3. As an example, in the case of housing under the conditions shown in note, the reflection coefficient $|\Gamma|$ =1,45 [68] in the frequency range of 0,7 GHz to 4,6 GHz.

NOTE The top cover of the housing is constructed of fibre reinforced plastic with diameter and thickness of approximately 600 mm and 50 mm, respectively. The housing in the underground is constructed of concrete with an internal space of height approximately 800 mm to 1 100 mm and of width and depth 600 mm. The road surrounding the base station has a three-layer structure and is composed of asphalt, crushed stone, and soil from the top. Dielectric constants of the concrete of the housing and the structures of the road were considered from dry to wet condition [68].

SAR measurements, see Clause B.5, are also possible for such type of BS installation.

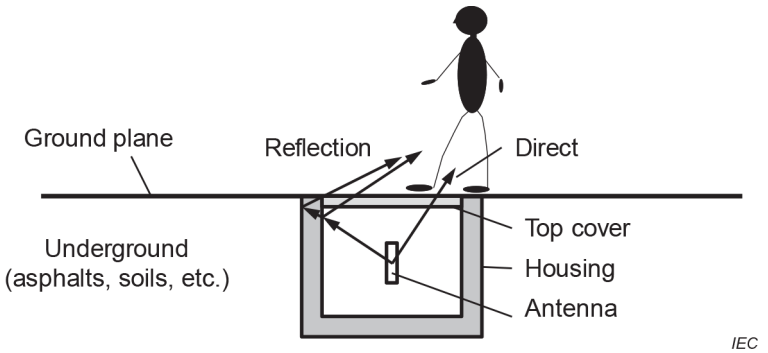


Figure B.4 – Reflections due to the presence of internal walls of the housing and surrounding asphalt and soil configuring a base station installed underground

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B.3.2 Measurement of RF field strength and power density

Figure B.5 shows a general representation of RF field strength or power density measurement. Figure B.6 shows practical examples of measurement equipment installation.

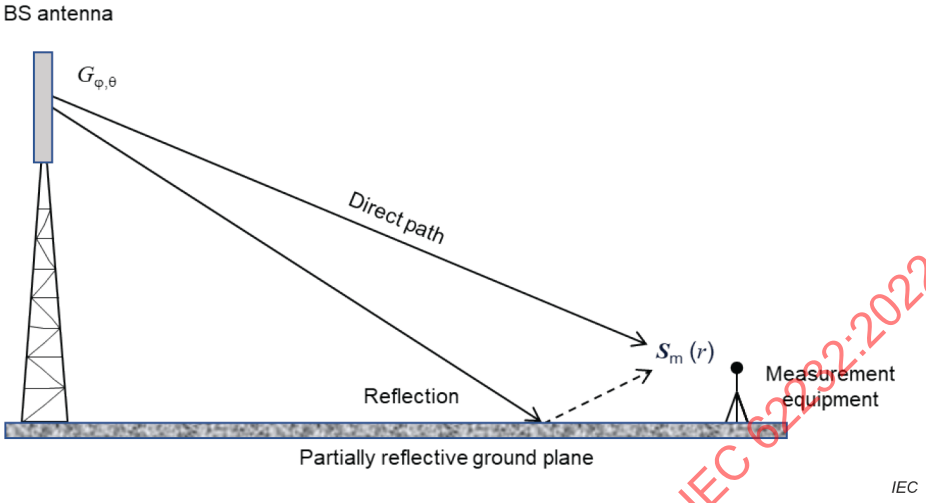
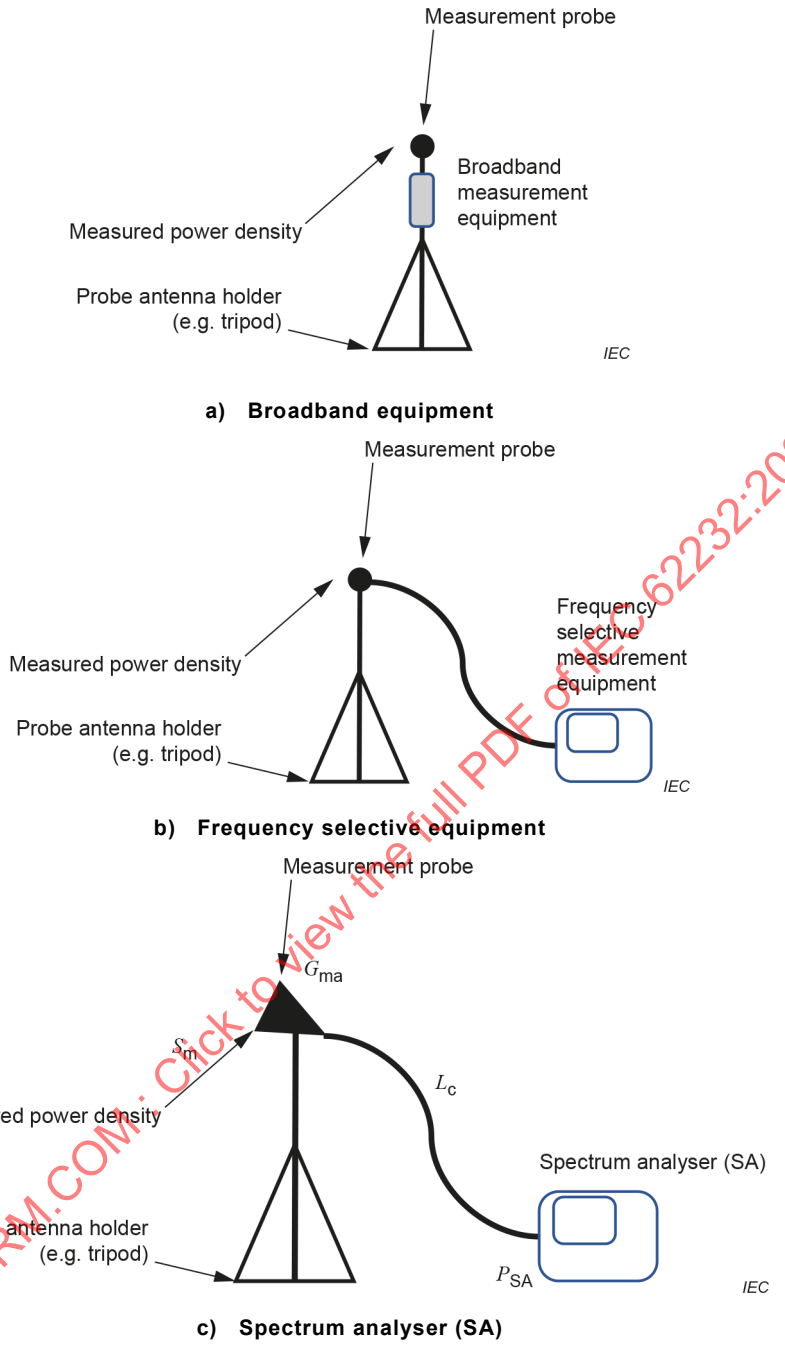


Figure B.5 – General representation of RF field strength or power density measurements

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Figure B.6 – Practical examples of measurement equipment installation

Measurements shall be performed as specified in Clause B.4. Broadband and frequency selective equipment provide direct reading of the RF field strength or power density, including ground reflections or multipath propagation. When using a spectrum analyser, the relation between the measured power and the antenna transmitted power, assuming free space conditions is given by the Friis formula, see Equation (B.9) and Equation (B.10). The relation between the power density and the power measured by the SA is provided in Equation (B.9). Ground reflections or multipath propagation can also be considered as specified in B.3.1.2.

$$P_{SA} = P_{BS} \cdot G_{BS} \cdot G_{ma} \cdot \alpha_c \cdot \left(\frac{\lambda}{4\pi \cdot r}\right)^2 \quad \text{(B.9)}$$

$$P_{SA} = S_m \cdot \frac{\lambda^2}{4\pi} \cdot G_{ma} \cdot \alpha_c \text{ or } S_m = \frac{4\pi \cdot P_{SA}}{\lambda^2 \cdot G_{ma} \cdot \alpha_c} \quad \text{(B.10)}$$

where

P_{SA} is the RF power measured by the SA;

P_{BS} is the BS transmitted power;

S_m is the measured power density;

α_c is the measurement cable attenuation;

G_{ma} is the gain of the measurement antenna;

G_{BS} is the gain of the BS;

λ is the wavelength of the RF signal;

r is the distance between the BS antenna and the measurement probe.

B.3.3 Spatial averaging

B.3.3.1 General

Evaluating the maximum RF field strength at a point can demonstrate compliance with both whole-body average and localized limits. However, in a non-plane wave RF field, comparing the maximum RF field strength or power density evaluated at a single point with the RF exposure limit can overestimate the whole-body RF exposure. Spatially averaging the RF field strength or power density in regions that a body occupies provides a better representation of the whole-body human exposure.

Spatial averaging implementation depends on the applicable RF exposure limit and regulations as described in 6.4.1.

The applicable whole-body exposure guidelines can specify limits for spatially-averaged RF field strength over the space occupied by the body of the exposed individual, as long as the localized RF exposure limits are not exceeded, see for example [1], [2], [3], [4]. Whilst the exposure ratio for the spatially-averaged field corresponds more accurately with the whole-body exposure ratio, it does not necessarily suffice to demonstrate compliance with the localized limits.

Spatial averaging shall be performed:

a) using a line or cross-sectional area that represents the volume occupied by a body around the evaluation location according to spatial averaging schemes described in B.3.3.2; and,

b) using the spatial averaging formulas specified in B.3.3.3.

The spatial distribution of the field at the position of a body depends on propagation conditions including reflections from objects in the environment [69], [70]. In case of exposure to multiple sources, multiple spatial averaging schemes, orientations and evaluation points can be applied around the evaluation location.

Information about the spatial averaging scheme(s), see B.3.3.2, employed for RF exposure evaluation shall be provided in the RF exposure evaluation report, see Clause 10.

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B.3.3.2 Spatial averaging scheme

Spatial averaging consists of evaluating the RF field strength or power density at N_p measurement points representing human exposure. Measurement points are those surrounding the evaluation location and located above the walking or standing surface. The spatial averaging scheme described in Figure B.7 provides examples for selecting the N_p measurement points. In cases of doubt or to resolve disputes, the reference spatial averaging method for whole-body exposure is the spatial average over nine points, see Figure B.7.

NOTE It is possible that the applicable regulations specify alternative spatial averaging schemes.

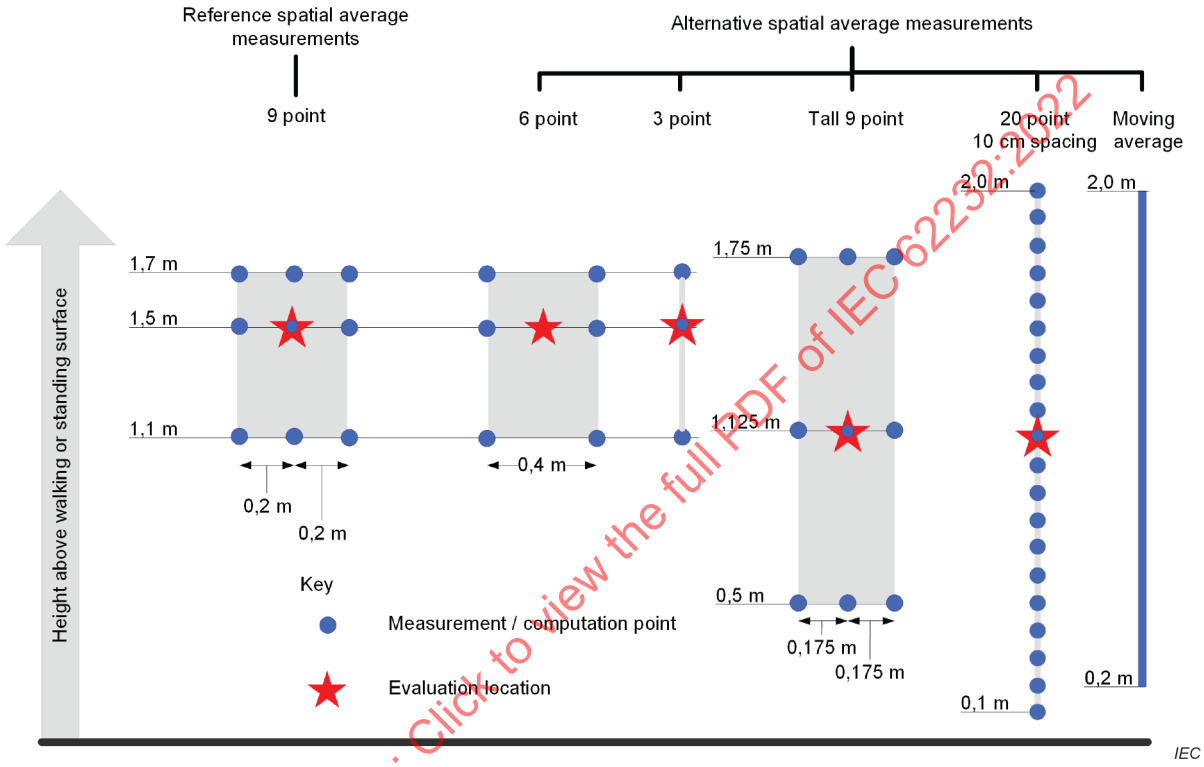


Figure B.7 – Spatial averaging schemes relative to walking or standing surface and in the vertical plane oriented to offer maximum area in the direction of the source being evaluated

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The orientation of the plane used for the reference method shall be based on the foreseeable exposure conditions at the evaluation location. For example, when evaluating exposure of pedestrians from a single source, the plane of the spatial averaging scheme should be vertical, including the evaluation location and oriented perpendicular to the direction of the source.

Depending on the applicable limits, spatial averaging of power density over smaller planar surfaces (e.g. 4 cm^2) might be relevant to accurately assess localized RF exposure when in close proximity to the EUT. IEC/IEEE 63195-1 provides guidance on averaging schemes relevant for localized power density at frequencies above 6 GHz. For separation distances from the EUT larger than 20 cm, the field distribution is typically nearly uniform over such small surfaces and localized power density is generally well approximated by the spatial-peak value [71]. More information on the applicability of spatial averaging is provided in Table 3, see 7.2.3.

Where spatial-peak RF exposure is relevant for the applicable RF exposure limits, the maximum RF field strength or power density at any of the measurement points shall also be considered, see Table 3.

The schemes shown in Figure B.7 are useful for evaluating RF field strength for determining human exposure in typical positions of the body (e.g. floor standing). In some circumstances where, for example, exposures occur whilst at elevated heights (e.g. on a ladder or other support structure), exposure evaluation shall be done for a realistic position of the body and foot support which provides maximum exposure (e.g. position the evaluation location in the main beam of the transmitting antenna).

As a special case, when a base station installed underground forms a service area on the ground, see B.3.1.4, it is possible that the exposure level is large at a height close to the ground surface. In such cases, the schemes shown in Figure B.7 can underestimate the exposure, assuming a relatively short person such as a child. It is possible to adapt the 20-point 10 cm spacing scheme in Figure B.7 to an N-point 10 cm spacing scheme, with the maximum height (0,1 × N m) being that of a small child and the evaluation location being at the centre. For example, the height used in the evaluation can be set to 0,96 m [72] for consistency with the small box shaped phantom in B.5.2.2.1, corresponding to N = 10, or 0,7 m, corresponding to N = 7, considering the average height of a one-year-old child [68].

B.3.3.3 Spatial averaging formulas

The spatially-averaged value of the RF field strength or power density at each evaluation location is determined using Equation (B.11):

$$\overline{E} = \sqrt{\frac{\sum_{i=1}^{N_\mathrm{p}} {E_i}^2}{N_\mathrm{p}}} \quad \text{or} \quad \overline{H} = \sqrt{\frac{\sum_{i=1}^{N_\mathrm{p}} {H_i}^2}{N_\mathrm{p}}} \quad \text{or} \quad \overline{S} = \frac{\sum_{i=1}^{N_\mathrm{p}} S_i}{N_\mathrm{p}} \tag{B.11}$$

where

$\overline{E}$ is the spatially averaged electric field strength at the evaluation location;

E_i is the RMS value of the electric field strength at the i-th measurement point;

$\overline{H}$ is the spatially averaged magnetic field strength at the evaluation location;

H_i is the RMS value of the magnetic field strength at the i-th measurement point;

N_p is the total number of measurement points for each evaluation location;

$\overline{S}$ is the spatially averaged plane wave equivalent power density at the evaluation location;

S_i is the plane wave equivalent power density at the i-th measurement point.

When using a frequency selective measurement probe or a spectrum analyser (SA), Equation (B.11) shall be implemented separately for each frequency band.

Clause G.11 contains informative direction on the error related to spatial averaging. Determination of error, statistical parameters, characterization of different spatial averaging schemes and environment are all discussed.

In some situations, the spatial distribution is dominated by the direct field from the antenna (e.g. source-environment region *-0) or in combination with a ground reflected wave (e.g. in open areas). Ideally, the spatially averaged field value should be determined from many evaluation points to obtain information on the variation in RF field strength.

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In a cluttered environment, the distribution is influenced by multiple reflections and diffraction and can create a highly non-uniform field distribution. A theoretical analysis in [69], based on the statistics of small-scale fading (random variations of the field around a local mean), provides some guidance on determining the uncertainty in the estimation of the spatial-average field from a limited set of spatial measurements.

B.3.3.4 Averaging around the spatial-peak field point

The method is shown in Figure B.8. The spatially averaged RF field strength or power density is determined by first scanning between 0,5 m and 1,75 m above walking or standing surface to find the spatial-peak RF field strength or power density value in the region. The peak and two additional measurements at points one wavelength vertically above and below are combined to determine the spatially averaged RF field strength or power density. This method is not specific to a typical or "standard" height adult human and it weights the result towards the spatial-peak RF field strength value.

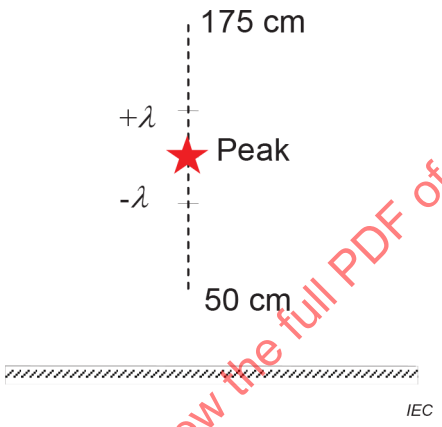


Figure B.8 – Spatial averaging relative to spatial-peak field strength point height

B.3.4 Time averaging

B.3.4.1 Applicability of time averaging

Time averaging is applicable where the RF field strength varies over time. Changing propagation conditions, variations of the transmitted power due to traffic variations, power control, or duty-cycle due to transmitter operation, are all scenarios where time averaging can be applied.

The applicable exposure standard or regulation generally specify the appropriate time-averaging period. Different time averaging periods can provide useful information but shall not be used for comparison with the applicable exposure limits.

Time averaging can be employed for push-to-talk (PTT) systems, where the BS transmits only when the user keys up the transmitter during simplex, or half-duplex, communication. When time averaging is implemented, duty-cycle data shall be considered as a subsequent correction if required for the evaluation purpose.

Time averaging is relevant for the implementation of the actual maximum approach as specified in 6.2.3, 8.4 and Clause B.9.

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B.3.4.2 Time averaging measurement method

The following steps shall be performed.

a) Determine when to perform the measurement; for example, conduct the evaluation during the highest RF field strength conditions – i.e. under maximum traffic conditions.

NOTE 1 Data logging over an extended period (day/week) can be useful in determining when to perform the time-averaged evaluation.

b) Specify the averaging time, for example, in accordance with the relevant exposure standard.

c) Specify the evaluation location; for example, use the sweep method, see B.4.2.5.2, to establish the location of spatial-peak RF field strength.

d) Perform the evaluation.

NOTE 2 Such measurements can be performed with portable data logging equipment adapted to the averaging time related to the applicable exposure limits. These can provide a "sliding" average (i.e. the instantaneous value of the average over a period of time ending at the present time and starting at the appropriate averaging time before the present).

B.3.4.3 Guidance on addressing time variation of signals in measurement

a) The following shall be considered when interpreting measurement data or defining the time at which the measurement is performed.

1) In operation and depending on the technology, the BS output power is likely to vary in time. Typically, the radiated power varies in accordance with overall traffic carried – often with a dependency on time of day, whether it is a working day or vacation, etc. There can be short-term variations in output power as traffic changes minute by minute and power control operates on shorter timescales. These variations can introduce uncertainty into sequential measurements performed at different locations. Long-term variations in RF field strength depend on traffic and are not determined during short-term measurement activities.

2) If the evaluation purpose is to measure the highest RF field strength, then short-term measurements should be made at times when communications traffic is heaviest, for example during a weekday evening rush hour when there is maximum human activity in the area around the BS. However, measurements of a stable reference signal, also called synchronization signal, can be made at any time. Extrapolation of exposure in accordance with the configured maximum or actual maximum is specified in Clause B.8 and examples are provided in Annex E.

3) At evaluation locations removed from the RF source, changes in propagation path can introduce fading.

b) Since measurements are normally made at different locations in a time sequence, the field variations in time and space tend to mix in the measurement result. This mixing is generally acceptable for spatially-time-averaged measurements. However, one of the following approaches can be employed to separate the spatial and temporal variations.

1) Repeat measurements at evaluation locations and examine the difference between repetitions as a function of time.

2) Fix a measurement antenna or isotropic probe at one location and observe how the readings change in time to isolate the temporal variation and handle as an influence factor (combined BS output power and propagation path time variations) in the uncertainty analysis.

3) Use a fixed measurement antenna or isotropic probe as a reference to correct the readings of a second measurement antenna or isotropic probe at the evaluation points.

4) Measure a stable reference signal from the EUT, see Annex E and use communications traffic data to determine the combined RF field strength for all signals as a function of time. Stable reference signal measurements can be made at any time. However, even the reference signal is subject to fluctuation due to changes in the propagation path.

5) Measure a stable reference signal from the EUT, see Annex E, over time to isolate the uncertainty influence factor of changes in propagation path over time from changes in BS output power.

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B.3.5 Comparing measured and computed values

Comparison of measured and computed values is generally performed for validation purpose, see for example Annex C. Measured and computed values shall be based on the evaluation methods described in Annex B taking into account both measurement and computational uncertainties.

B.3.6 Personal RF monitors

Personal RF monitors are generally small portable handheld or body worn units that can be used by workers as safety equipment to identify potentially hazardous RF sources in their workplace. These units enable workers to move freely through areas of varying and unknown RF field strengths with the expectation that the equipment provides some form of warning before the RF exposure to the user exceeds the applicable threshold. A variety of personal RF monitors are available. They cater for a range of frequency bands, exposure standards, detector polarities, field characteristics, and accuracy specifications.

Personal RF monitors should not be used for RF exposure compliance assessment as specified in Clause 6 for a number of reasons; not least of which is the interaction between the user's body and relative position of the unit and its effect on the indicated exposure level.

Personal RF monitors can trigger the need for further investigations to be carried out by a trained surveyor using calibrated RF survey equipment.

B.4 RF field strength and power density measurements

B.4.1 Applicability of RF field strength and power density measurements

RF field strength and power density measurements are applicable in all source-environment plane regions, see Annex A, in accordance with the criteria specified in Table 3. Frequency selective measurements are recommended where there is more than a single frequency present, see Table A.9.

B.4.2 In-situ RF exposure measurements

B.4.2.1 General requirements

B.4.2 is generally applicable to both RF field strength and power density measurements. The following checks shall be performed.

a) The measurement equipment shall meet the requirements of B.4.2.2.

b) Determine as many of the known characteristics of the sources of the RF fields as possible and estimate their likely propagation characteristics.

c) Estimate the expected RF field strength using the basic computation methods in Clause B.6.

d) Verify that out-of-band and/or strong ambient signals do not create spurious responses in the measurement equipment.

NOTE 1 Co-band sources located adjacent to the EUT, or low frequency fields from high-tension power lines, can affect (especially broadband) instruments.

e) Establish if the reading is caused by the measurement equipment noise;

f) Determine the optimum measurement equipment settings.

NOTE 2 See Clause E.3, the measurement equipment manufacturers' specifications, and measurement equipment manufacturers' guidelines.

g) Where a shaped frequency response broadband equipment is used, check that its summation algorithm and frequency calibration are consistent with the requirements of the relevant standard.

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h) If more than one measurement antenna or isotropic probe is required to cover a specified frequency range, then the TER shall be determined in accordance with 8.5 and the RF field strength shall be determined using Equation (B.12):

$$E = \sqrt{\sum_{i=1}^{N} E_i^2} \quad \text{or} \quad H = \sqrt{\sum_{i=1}^{N} H_i^2} \quad \text{or} \quad S = \sum_{i=1}^{N} S_i \tag{B.12}$$

where

E is the electric field strength at the measurement point;

E_i is the RMS value of the electric field strength measured by the i-th measurement antenna or isotropic probe at the measurement point;

H is the magnetic field strength at the measurement point;

H_i is the RMS value of the magnetic field strength measured by the i-th measurement antenna or isotropic probe at the measurement point;

N is the number of measurement antennas and isotropic probes;

S is the plane wave equivalent power density at the measurement point;

S_i is the plane wave equivalent power density measured by the i-th measurement antenna or isotropic probe at the measurement point.

NOTE 3 For broadband measurement equipment, the above summation can result in a systematic overestimation of the RF field strength if the measurements have overlapping frequencies. This can be avoided by using frequency selective measurements.

i) Consider the location of the source and RF propagation path during surveys to minimize the influence of the body on the measurement. Handheld measurements can be used to get a preliminary survey of the area in order to select the measurement points. Refer to the manufacturer's specifications for the minimum distance between the measurement probe tip and the body of the surveyor as well as any reflecting object. For handheld measurements, the uncertainty due to the scattering of the RF field by the surveyor's body shall be minimized by:

1) holding the probe or antenna away from the surveyor's body (a separation of at least 50 cm should be maintained between the measurement antenna or isotropic probe and the surveyor's body);
2) pointing the probe towards the source;
3) ensuring that the surveyor's body is not along the direct line of propagation between the source and the measurement probe (either in front of or behind);

j) The uncertainty due to mutual coupling between measurement antenna or isotropic probe and physical objects (e.g. walls, floor, ceiling, furniture and other objects) shall be considered:

1) measurements at separation distances down to 20 cm are acceptable dependent on the measurement frequency and measurement equipment. But when separation distances are less than 50 cm, this influence on the measurement uncertainty shall be included in Table B.7 and Table B.8, see B.4.4;
2) where the size of the receiving elements of the measurement antenna or isotropic probe do not exceed a dimension of 0,4 m, and where a separation distance greater than or equal to 50 cm is maintained, the influence on measurement uncertainty need not be considered.

k) The uncertainty due to high gradients in the RF field strength (e.g. quasi-static near-field) in proximity to RF radiators or re-radiators shall be considered if the minimum separation distance between the measurement antenna or isotropic probe and RF radiators or re-radiators is less than three times the largest dimension of the measurement antenna or isotropic probe.

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l) In a complex field, local minima and maxima occur within a relatively small area. Factors such as shadowing, reflection and diffraction, together with the radiation pattern characteristics of transmitting antennas, can be involved. The effects of fast fading, however, can be estimated and accounted for by spatial sampling and averaging (described in 6.4).

For additional information see, for example, [73].

B.4.2.2 In-situ measurement equipment requirements

Equipment used for in-situ measurement shall be calibrated at multiple frequencies to achieve the declared uncertainty of the equipment over the measurement frequency range, including lower and upper band extremities. This is achieved either as a whole system or by calibration of all the individual parts of the system. For signals with high crest factors or combinations of several signals, additional calibration can be necessary to assess uncertainty.

Where specific demodulation capabilities are used, measurement equipment shall also be calibrated for the parameters of interest (e.g. for WCDMA the CPICH signal and signal-to-noise ratio, see Annex E).

Table B.5 summarizes the minimum performance requirements for a broadband measurement system used for RF exposure evaluation. Table B.6 summarizes the minimum performance requirements for a frequency selective measurement system used for RF exposure evaluation.

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Table B.5 – Broadband measurement system minimum requirements

Parameters	Requirements
Frequency response	• ±1,5 dB (from 600 MHz to 6 GHz) • ±3 dB (for the frequencies to be measured < 600 MHz and > 6 GHz)
Lower detection level [a]	• 17 dB below the lowest value specified in the applicable exposure limits or regulation in the frequency range covering the EUT and ambient sources, see B.4.2.6
Dynamic range	> 25 dB
Linearity	±1,5 dB
Probe isotropy [b]	< 2,5 dB for an isotropic probe

[a] This allows to determine contributions of relevant sources, (i.e. 13 dB range considering an ER of 0,05) including a 4 dB margin corresponding to the target uncertainty, see 6.3.6. This corresponds to a power density of 40 mW m^{-2}, E-field strength of 4 V m^{-1} or H-field strength of 10,6 mA m^{-1} considering general public exposure limits in ICNIRP-2020 [1], ICNIRP-1998 [2], or IEEE Std C95.1-2019 [3]. This also corresponds to a power density of 26 mW m^{-2}, E-field strength of 3,1 V m^{-1} or H-field strength of 8,2 mA m^{-1} considering general public exposure limits in Safety Code 6 [4].

[b] Probes and measurement antennas with isotropic response are recommended. Single-axis (e.g. dipole) and directional measurement antennas are permitted provided that the measurements are post processed to obtain the total RF field strength (equivalent to a measurement with an isotropic probe or measurement antenna).

Table B.6 – Frequency selective measurement system minimum requirements

Parameters	Requirements
Frequency response	• ±1,5 dB (from 600 MHz to 6 GHz) • ±3 dB (for the frequencies to be measured < 600 MHz and > 6 GHz)
Lower detection level [a]	• 44 dB below the lowest value specified in the applicable exposure limits or regulation in the frequency range covering the EUT and ambient sources, see B.4.2.6 • Signal-to-noise ratio of at least 10 dB in the measurement bandwidth
Dynamic range	> 60 dB
Linearity	±1,5 dB
Probe isotropy [b]	• < 2 dB (< 900 MHz) • < 3 dB (from 900 MHz to 3 GHz) • < 5 dB (> 3 GHz)

[a] This allows to determine contributions of sources of interest (i.e. 40 dB range considering an ER of 0,0001) including a 4 dB margin corresponding to the target uncertainty, see 6.3.6. This corresponds to a power density of 0,08 mW m^{-2}, E-field strength of 0,17 V m^{-1} or H-field strength of 0,46 mA m^{-1} considering the general public exposure limits in ICNIRP-2020 [1], ICNIRP-1998 [2] or IEEE Std C95.1-2019 [3]. This also corresponds to a power density of 0,05 mW m^{-2}, E-field strength of 0,14 V m^{-1} or H-field strength of 0,37 mA m^{-1} considering general public exposure limits in Safety Code 6 [4].

[b] Probes and measurement antennas with isotropic response are recommended. Single-axis (e.g. dipole) and directional measurement antennas are permitted provided that the measurements are post processed to obtain the total RF field strength (equivalent to a measurement with an isotropic probe or measurement antenna).

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B.4.2.3 Broadband in-situ measurements

B.4.2.3.1 Applicability of broadband in-situ measurements

Broadband measurements provide the sum of all signals over the frequency range of the probe without distinguishing the contribution of different frequencies (whether from the EUT or from ambient sources). These can be an instantaneous or time-averaged RF field strength value.

The method provides an informative environmental RF field strength reading as observed at the time of measurement and is adequate for monitoring the RF field.

A broadband measurement is suitable for determining overall levels in the environment and can be helpful in determining if a more comprehensive measurement using the frequency selective method, see B.4.2.4.2, is required.

Extrapolation using a broadband probe is not recommended and shall only be performed under the conditions specified in B.8.2.

B.4.2.3.2 Broadband in-situ measurement method

Broadband in-situ measurements require an isotropic broadband survey equipment that has measurement and frequency ranges adequate to measure the RF field strength estimated during the site analysis, see 6.3.3, and fulfils the requirements in B.4.2.2.

To provide a direct read-out expressed in terms of the relevant total exposure ratio, see B.4.2.3.3.2, the frequency response of the probe shall either be flat over the required frequency range (Table B.5) or be frequency dependent to match the relevant frequency dependent exposure limit.

To evaluate the highest RF field strength or the RF field strength at discrete points in a region, a search shall be performed using the handheld sweep method, see B.4.2.5.2, or tripod procedure, see B.4.2.5.3.

If required, spatial averaging of the field can be performed, see 6.4.1 and B.3.3).

The evaluation shall investigate temporal variations in the field; either to obtain a stable indication of the RF field strength or to fulfil averaging time requirements required by the applicable exposure limits used for compliance assessment, see B.3.4.3.

B.4.2.3.3 Interpreting measurements over multiple frequency bands

B.4.2.3.3.1 Flat frequency response probe

If signals are being radiated over multiple frequency bands (e.g. 900 MHz and 1 800 MHz) and the probe is capable of operating accurately over the aggregate signal band then the lowest applicable exposure limit for the frequencies present shall be used to determine the combined exposure ratio expressed as a fraction/percentage of the applicable RF exposure limit.

The use of the lowest exposure limit can lead to an over estimation of exposure. As an alternative, it is recommended to implement frequency selective measurements, see B.4.2.4.

B.4.2.3.3.2 Shaped frequency response probe

The measurement equipment sums the individual measurement levels at the frequencies of the various sources and presents the result in the form of an exposure ratio, for example as a percentage of the applicable limit.

B.4.2.4 Frequency selective in-situ measurements

B.4.2.4.1 Applicability of frequency selective in-situ measurements

These techniques employ spectrum analysis or channel decoding to isolate and identify the BS source and ambient frequencies. The method shall be used:

a) to discriminate signals at different frequencies;

b) when ambient fields are comparable to, or likely to exceed, the level of the BS source;

c) when information is needed to enable the precise extrapolation from the evaluation configuration to the assessment configuration;

d) in case of in-situ RF exposure assessment, when the power density level is above a given threshold, for example 100 mW m^{-2}, as described in 6.3.

B.4.2.4.2 Frequency selective in-situ measurement method

When using frequency selective equipment, it shall cover the frequency range of the signals to be evaluated, see Annex E. Measurement over a wide range of frequencies can in some cases require more than one measurement antenna.

The RF field strength measurement shall consider contributions from all directions/polarizations. An isotropic antenna is best suited to this. Other antennas can be used in accordance with the following provisions.

a) Single-axis (e.g. dipole) can be used to obtain the total RF field strength by positioning the probe in three orthogonal directions and summing the individual measured results.

b) A directional measurement antenna or probe can be used to separate contributions from different directions (not source region I). These contributions shall be summed to determine the total RF field strength. However, this value provides an overestimation of the true level.

c) A directional antenna can be used for the handheld sweep method provided it is oriented to read the maximum RF field strength value.

Correlation between results obtained using isotropic and non-isotropic antennas can be influenced by the presence of strong multi-path signals.

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An initial broad-spectrum scan shall be performed to identify signals to be considered for subsequent analysis. For these signals (e.g. high level), the measurement resolution shall be increased by centring on the signal frequency and performing a specific measurement of each signal.

Each of the relevant frequency bands to be investigated shall be analysed to determine the optimum settings for the selective meter. The resolution bandwidth setting shall take into account the BS signal types and, when appropriate, ambient fields. Annex E provides technology-specific information useful for determining selective meter settings.

Additional processing is required for the measurement of time-varying signals; for example, when a communication systems output power is a function of the number of active users. Temporal variations in the field shall be investigated; either to obtain a stable indication of the RF field strength or to fulfil related averaging time requirements for determining compliance with the applicable exposure limit. B.3.4.3 provides additional guidance on evaluating time-varying signals.

To evaluate the highest RF field strength or the RF field strength at discrete points in a region, perform a search using a handheld RF field strength measurement procedure, see B.4.2.5.2, or tripod RF field strength measurement procedure, see B.4.2.5.3. Additionally, spatial averaging of the field can be performed, see 6.4.1 and B.3.3.

To obtain an estimate of the maximum possible level, extrapolation of the result shall be performed if required, see Clause B.8. This post-processing is required to determine a time-independent maximum possible RF field strength that in turn can be used to establish compliance boundaries around antennas.

B.4.2.5 In-situ measurement procedures

B.4.2.5.1 Determining the RF field strength or power density at fixed evaluation points of interest

Measurements shall be made using a measurement system whose response is calibrated as a function of frequency. If a non-isotropic measurement antenna is used, it shall be oriented to read the maximum value (when performing a search for a maximum RF field strength or power density value and/or its location).

In the case of single axis probe or measurement antenna, it shall be rotated to obtain the three orthogonal components of the field and the measurement result summed (root sum square) to obtain the total RF field strength or power density. Since the measurements are performed in different time intervals, time-varying fields can lead to an additional uncertainty on the assessment of the total field level.

B.4.2.5.2 Sweeping a volume to determine a RF field strength or power density value of interest and/or its location

The handheld sweep method shall be used in-situ to:

- determine the locations with the maximum RF field strength or power density value of interest within the measurement area, see 6.3; or

  NOTE 1 The handheld sweep method can be used to determine the point of investigation (PoI, see 6.3.4) or locations for subsequent investigation using spatial averaging techniques.

- determine the maximum RF field strength or power density value in a region without requiring information about the location.

  NOTE 2 In the case of an uncluttered environment, the maximum RF field strength or power density from a single source is likely to be found in the main beam of the antenna.

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The measurement antenna (or isotropic probe) shall be moved smoothly throughout the region avoiding proximity to objects. Measurements shall be performed at and around a height of 1,5 m above the walking or standing surface within the measurement area. The measurement antenna (or isotropic probe) shall be moved vertically (up to 2 m) and horizontally throughout the region under test while observing the equipment display in order capture any maxima. Careful sweeping is necessary around the location where the value of interest is expected.

When using a frequency selective equipment:

a) the RMS detector shall be selected;

b) the frequency scan time of the spectrum analyser shall be considered;

c) the sweep shall be stopped at dwell points to record any maxima;

d) a full frequency scan of the entire range of interest shall be completed at each dwell point to identify peaks and their respective levels;

e) the frequency span shall be chosen according to Clause E.3 so as to provide an accurate evaluation of the RMS value of the signal.

NOTE 3 It is possible that frequencies need to be separated into various groups (bands) to identify the levels of emissions from these individual bands.

B.4.2.5.3 In-situ measurements using tripod-supported instrument/antenna

The measurement equipment and general methodology specified in B.4.2.4 are applicable to the tripod method; however, influences of the surveyor's body are reduced. A support/mounting system that is non- or minimally perturbing to the field shall be used to hold the measurement antenna or isotropic probe in position during measurements. (e.g. wooden tripod)

A scan of the region under investigation using the handheld sweep method, see B.4.2.5.2, shall be performed to determine the locations of significant RF field strength levels and limit the size of the investigative volume. An area/volume around these locations shall be selected and divided into a suitable measurement grid to enable a finer investigation of the field. The resolution of such a grid shall be suitable to distinguish all field gradients and capture all field peaks.

The dimensions of the measurement antenna or isotropic probe determine the smallest resolution applicable for the measurement grid.

B.4.2.5.4 In-situ measurements with emulated BS load profiles

B.4.2.5.4.1 General

An approach to perform in-situ measurements without detailed information about the EUT is outlined below. This approach yields RF exposure results for different BS loading conditions and is particularly useful when measurements are performed in networks characterized by extremely low traffic (e.g. when a new technology is deployed). The approach uses a UE to generate different BS loads. The UE shall be placed so that the BS serving beam(s) are directed towards the evaluation location. If the measurement's objective is to evaluate more than one BS, the procedure should be repeated with the UE connected to the other BS of interest.

The following measurement setups should be configured to represent three different types of BS load profiles (also called utilization scenarios):

a) Non-specific BS load profile: Time averaged measurement (e.g. 6 min) without any traffic serving the UE located close to the evaluation location.

b) Typical BS load profile: Time averaged measurement (e.g. 6 min) while streaming a video (e.g. 4K HD), livestreaming TV, or downloading a file (e.g. 1 GB data file) on a UE close to the evaluation location so that it remains in the same beam.

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c) High BS load profile: Time averaged measurement (e.g. 6 min) while a continuous high bit rate data stream (e.g. UDP downlink transfer) is transmitted in the downlink direction towards a UE close to the evaluation location. If continuous downlink traffic cannot be generated for the entire time-averaging period (e.g. 6 min), reduce the time-averaging period to a more suitable window (e.g. 1 min) such that only RF exposure due to downlink traffic is measured. Multiple UEs can be placed in the same position to load the BS if one single UE is deemed insufficient.

Measurements are performed using a UE, a spectrum analyser and suitable antenna probe. The measurement equipment should meet the requirements specified in B.4.2.2. When multi-bands are being assessed at the same location, the UE should be capable of locking onto each frequency band such that the appropriate base station sector gets loaded with traffic. In the absence of BS counters, the spectrum analyser should be used to confirm the increase in traffic loading across the frequency band being assessed.

For BS using beamforming, the presence of multiple spatially separated UEs impacts the ability to direct a single maximum gain traffic beam towards the point of RF exposure measurement. Without the availability of BS counters, see B.9.5, or antenna pattern information, the presence of other UEs in the area is not known and therefore the generation of maximum exposure from beamforming should be performed on a best effort basis.

For TDD systems, it is important to minimize the impact of uplink traffic on the measured RF exposure. This can be achieved by utilizing a UDP downlink transfer or placing the UE away from the measurement equipment. A distance of 1,5 m is deemed sufficient when using UDP downlink transmission because of the limited uplink emissions from the UE. When measuring exposure from a BS in line-of-sight (LoS), shorter distances can be considered provided that the uplink signal contribution on the measurement is negligible compared to the overall measurement uncertainty. If it is not possible to place the UE away from the measurement probe, then absorbing material can be placed between the probe and the UE to reduce the impact of the UE on the measurement probe. When using a directional probe, if its aperture is pointed away from the UE, the impact of uplink exposure is deemed to be negligible at any distance. Measurement techniques (e.g. E.8.2.1.3) or equipment able to discern between the uplink and downlink contributions do not require any specific consideration on the separation between the probe and the UE.

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B.4.2.5.4.2 Measurement with high BS load profile

The procedure to measure the RF exposure for a high BS load profile is outlined below. These measurement steps also apply to the non-specific and typical BS load scenarios.

a) Identify the BS carrier centre frequency.

b) Identify the BS applicable channel bandwidth.

c) Configure the spectrum analyser to measure the full BS carrier; if measurements are performed in a sub-band of the channel bandwidth, scaling should be applied. Measuring in a sub-band might be necessary if the UE cannot support wideband operation (e.g. NR allows UE to only operate in a sub-part of the bandwidth). In other cases, sub-band measurements allow to overcome possible limitations in the spectrum analyser (e.g. in terms of maximum resolution bandwidth).

d) Configure the high BS load scenario using an appropriate network performance tool (for example using iPerf [6] tool utilizing a UDP downlink transfer).

e) Measure the channel power using the spectrum analyser – set the channel markers to either side of the BS carrier.

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6 iPerf is the name of a tool supplied under BSD License (see https://iperf.fr/contact.php#authors). This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent tools can be used if they can be shown to accomplish the same tasks and lead to the same results.

f) In the case of a DSS signal, ensure that both technologies are tested according to B.8.6, or choose the technology that ensures the maximum configuration;

g) In case of a TDD signal, when the measurement technique does not allow to separate uplink and downlink exposure contributions, place the UE at least 1,5 m away from the probe as described in B.4.2.5.4.1 so that the UL contribution from the UE can be neglected.

h) The measurement duration depends on the measurement scenario. For the high BS load scenario, it is unlikely that the high-level signal remains stable for the full averaging time T_{avg} period (e.g. 6 min). Therefore, it is possible to use a lower time-averaging period, such as 1 min or 2 min, provided that the level averaged over the lower time-averaging period remains stable within ±10 % for the duration of the measurement. For other BS load scenarios, the duration of the measurement shall be T_{avg} or more.

i) Record the value of the time-averaged received signal and any other relevant measurement characteristics.

For high-capacity BS being evaluated under the high BS load scenario, care should be taken to select an appropriate download setup in order to reach the maximum BS load. Results should be compared with realistic expectations for the site type. The test conditions should be reported.

B.4.2.6 Guidance on determining ambient fields

B.4.2.6.1 Overview

The level of RF ambient fields shall be evaluated in locations within the domain of investigation (DI) where people can be exposed to RF fields from the EUT. The ambient fields from relevant sources shall be expressed as total exposure ratio using the summation formulas specified in 8.5.

B.4.2.6.2 Ambient radio source identification

Ambient fields from relevant sources shall be identified through visual inspection, consultation of available user databases (public or site owner), information from the site owner, as well as broadband (B.4.2.3) or frequency selective (B.4.2.4) measurements.

Categorize the RF sources as either being "collocated" or "remote" from the BS. Collocated RF sources are those located on the same antenna support, for example mast, rooftop or within the same transmitter compound or room as the BS. All other sources are "remote".

When evaluating the exposure ratio from the EUT combined with the ambient fields, it is acceptable to reduce the number of signals requiring precise evaluation by specifying appropriate significance criteria.

B.4.2.6.3 Selecting ambient field evaluation locations

B.4.2.6.3.1 Collocated sources

The ambient field level from these sources is likely to vary considerably over the evaluation area near the BS. The ambient field shall be evaluated at all locations where the BS fields are evaluated.

B.4.2.6.3.2 Remote sources

For RF fields from sources located at some distance from the BS, it is expected that there is little variation in RF field strength over the evaluation area arising from the source antenna directivity or small variations in distance from the source to the farthest evaluation location. There are, however, likely to be significant variations in RF field strength as a result of propagation affects, e.g. scattering and fading.

For the set of radio sources to be considered, a point shall be chosen that is clear of clutter as near as possible to the area of evaluation (e.g. on roof-top and/or in area of evaluation away

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from local clutter), or for calculation purposes at a point above the area of evaluation where free space propagation can be assumed.

a) This location should be used for evaluation of the ambient field if it is representative for all radio sources based on the following, see B.4.2.6.4:
   1) the distance from the ambient evaluation location to any BS evaluation location is less than 40 times the distance to the ambient source, see B.4.2.6.4.2;
   2) the ambient source is not highly directional.
b) For any radio sources not completely covered by this "master" evaluation location, select additional evaluation locations such that criteria in B.4.2.6.4.3 are met, for example:
   1) between the source and the area of evaluation; or
   2) additional evaluation locations in the clear, including the nearest point on the area of evaluation to the source.

B.4.2.6.3.3 Description

Evaluate the RF field strength for each ambient BS source in accordance with the evaluation protocol established in 6.3. For other RF sources, evaluate the RF field strength in accordance with the appropriate international standards, e.g. IEC 62311.

B.4.2.6.4 Proof of non-collocated source evaluation location selection criteria

B.4.2.6.4.1 Principles

A minimum number of evaluation locations shall be selected when establishing maximum case exposure ratios for ambient radio sources remote from the evaluation location.

The RF field strength determined at an evaluation location is deemed to represent conservatively the maximum exposure ratio for a radio source over an area described by a circle of radius δr provided:

a) the selected evaluation location is substantially clear of local clutter;
b) the variation of the exposure ratio is less than 5 % due to the difference in path length;
c) any variation in directivity of the radio source antenna based on free-space propagation can be ignored in the area containing the evaluation locations.

B.4.2.6.4.2 Establish criteria for separation of source evaluation locations considering distance to radio source

The distance between two evaluation locations should be based on a 5 % change in exposure ratio derived from the simple spherical formula, see Equation (B.1).

The power density S, from the remote source is given by Equation (B.13):

$$S = \frac{A}{r^2} \tag{B.13}$$

where

r is the distance to the remote source;

A is a constant when there is no significant change in directivity over the area being assessed (e.g. within 3 dB).

NOTE The value of A depends on the unit for r (e.g. m or km).

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Consider Figure B.9, moving a small distance δr towards the source (most critical condition) then the power density S is increasing by δS such that Equation (B.14) gives:

$$S + \delta S = \frac{A}{(r - \delta r)^2} \tag{B.14}$$

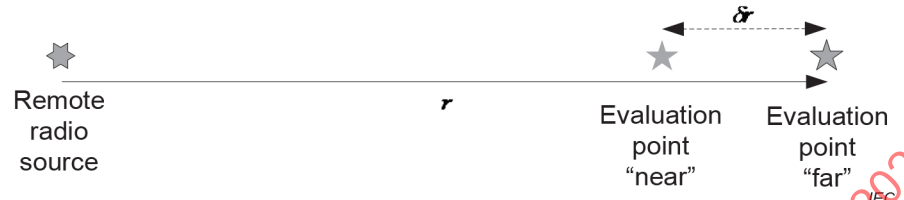


Figure B.9 – Evaluation locations

For a 5 % increase in S over distance δr gives Equation (B.15):

$$\frac{S + \delta S}{S} = 1{,}05 \tag{B.15}$$

Using Equation (B.13) and Equation (B.14) in Equation (B.15) yields Equation (B.16):

$$\frac{r^2}{(r - \delta r)^2} = 1{,}05 \tag{B.16}$$

The ratio X required is given by Equation (B.17)

$$X = \frac{r}{\delta r} \tag{B.17}$$

Substituting for X in Equation (B.16) and solving gives X = 41,49.

For a real world (and probably cluttered) environment, the power density S decays with a power factor in Equation (B.13) greater than 2. For two evaluation locations oriented in any other direction, S changes more slowly with δr. Therefore, a factor of 40 is appropriate for simplicity – i.e. provided the radio source is at a distance 40 times the distance between evaluation points, a single evaluation is all that is required.

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B.4.2.6.4.3 Establish criteria for separation of source evaluation locations considering distance to radio source

Now consider Figure B.10 for two evaluation locations at constant r but varying direction φ relative to the radio source.

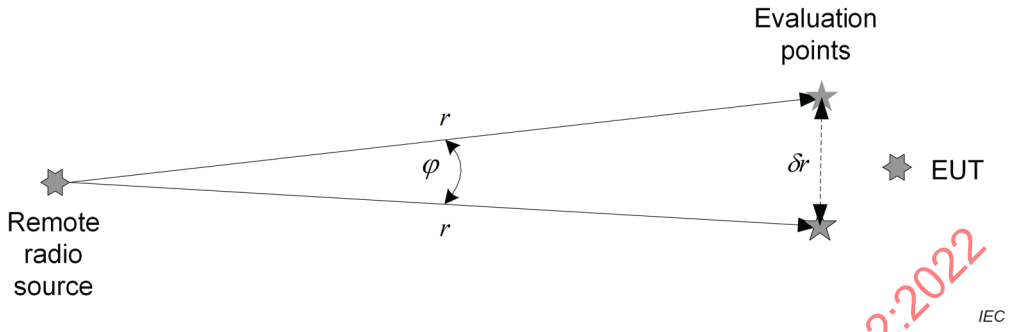


Figure B.10 – Relationship of separation of remote radio source and evaluation area to separation of evaluation points

For a source at a distance 40 times the separation between two evaluation locations is given by Equation (B.18) and Equation (B.19):

$$r = 40 \times \delta r \tag{B.18}$$

and

$$\varphi = 2 \times \tan^{-1} \frac{(\delta r / 2)}{40 \times \delta r} = 1{,}4° \tag{B.19}$$

Such a value is small enough to be disregarded except for highly directional (horizontal pattern) antenna sources deployed at the higher microwave frequencies. In those cases, the clutter variation is likely to be dominant and the maximum gain condition applicable for the area of evaluation should be used.

EXAMPLE 1

In an area of evaluation 15 m by 20 m, the maximum distance, d, between any two points is:

$$d = \sqrt{15^2 + 20^2} = 25 \text{ m}$$

For a radio source to be evaluated based on a single evaluation location, it shall be a distance of at least r from the area of evaluation, where

$$r = 40 \times 25 = 1\,000 \text{ m}$$

EXAMPLE 2

For a selected evaluation location 2 km from the nearest ambient radio source under investigation, an evaluation is valid for the parts of an area under evaluation extending to a distance d from the evaluation location:

$$d = \frac{2000}{40} = 50 \text{ m}$$

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B.4.3 Laboratory based RF field strength and power density measurements

B.4.3.1 General

The methods and requirements are applicable for direct or indirect measurements of the E-field strength, H-field strength, or power density from base stations operating in the entire frequency range covered by this document (110 MHz to 300 GHz), in the near-field as well as in the far-field region.

B.4.3.2 Requirements

B.4.3.2.1 General requirements

The measurement system for evaluating RF field strength or power density typically consists of electronic measurement equipment, field probe(s), a scanning system, an EUT holder and necessary post-processing software. Power density and RF field strength measurements are performed in free space in the absence of the body.

E-field strength, H-field strength, or power density can be measured directly at the evaluation points or otherwise obtained by means of field reconstruction techniques, based on scanning of the field in a suitable measurement region.

In source region I of the EUT there is no simple relationship between E-field strength and H-field strength. Therefore, both fields shall be determined either by measuring them separately or by calculating one field from the amplitude and phase of the other field. Within source regions II and III the plane-wave equivalent approximation can be used.

B.4.3.2.2 EUT configuration for RF field strength and power density measurements

If the EUT is a BS with integrated antenna(s), it shall use its internal transmitter(s), the normal power supply, and the original antenna(s). Alternatively, a signal generator or a synthesizer and amplifier can replace the transmitter that supplies power to the antenna input, provided that this does not change EUT performance, including transmitted power and power density distributions, or that the impact of power density assessment uncertainty is properly evaluated and remains acceptable. However, the entity performing the EUT configuration also needs to be aware of applicable regulations. In any case the BS shall be configured in accordance with the specifications provided by the manufacturer, and the output power and frequency (channel) shall be controlled by using an internal test programme or an appropriate external equipment.

If the BS is intended for use with external antenna(s), the same requirements apply, but the BS can be replaced with a transmitter providing the same RF output power to the antenna connector and frequency as the BS under evaluation. The entity performing the EUT configuration also needs to be aware of applicable regulations.

The appropriate operating modes of the EUT (e.g. modulation, source coding, channel bandwidth, etc.) shall be selected for testing taking into consideration different output power levels, such that maximum RF field strength or power density is assessed. When standardized conformance test models exist (e.g. 3GPP E-TM 3.1 for LTE) these shall be used for testing and the test model corresponding to the maximum RF output power condition shall be selected. If the EUT is tested in a lower power configuration, scaling shall be performed to obtain RF field strength or power density corresponding to the maximum output power level. A continuous wave (CW) signal can be used provided that the power is adjusted to produce a conservative result.

RF field strength and power density shall be measured at the centre frequency. If the bandwidth of the transmit frequency band for the EUT exceeds 5 % of the centre frequency, measurements at the lower and upper frequencies shall also be performed. If the EUT can operate with different channel bandwidths, the bandwidth leading to the maximum transmitted power shall be selected. If the EUT is tested in a lower power configuration, scaling to the maximum power shall be performed.

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B.4.3.2.3 Measurement requirements

The following requirements shall be addressed.

a) RF field strength or power density shall be selected according to Table 3 and measured in different directions and distances in accordance with 6.1.5.2 to determine the compliance boundaries.

b) If whole-body spatial averaging is to be applied, the spatial averaging schemes in B.3.3.2 shall be used. Guidance on averaging over smaller planar surfaces (e.g. 4 cm^2) is provided in IEC/IEEE 63195-1.

c) RF field strength measurements in source region I shall be based on the magnitudes of both E-field strength and H-field strength.

d) Power density measurement in source region I shall be based on evaluation of both amplitude and phases of the E-field strength and H-field strength components.

e) Field reconstruction can be used to derive one field from the other field (i.e. derive H-field strength from E-field strength, or vice versa). Field reconstruction methodologies for the power density are documented in IEC/IEEE 63195-1.

f) If the plane-wave equivalent approximation is applicable (source region II and III), measurement of the magnitude only of one field (E or H) can be used to determine the RF field strength of the other field and power density.

g) For EUTs with multiple antennas or multiple transmitters (with single or multiple antennas) transmitting simultaneously, the RF field strengths or power densities shall be combined in accordance with 8.5.

h) The expanded uncertainty with a confidence interval of 95 % shall not exceed 2 dB for the amplitude of the RF field strength and for power density. If the uncertainty is larger than 2 dB the difference shall be added to the evaluation result before comparison with the applicable exposure limit in accordance with the procedure in IEC 62311. If the relative uncertainty is less than 2 dB, then the measured value shall be compared directly with the applicable limit.

i) The required spatial resolution depends on the field characteristics and the measurement methodology. For instance, for systems based on field reconstruction, the measurement sampling interval shall be set in accordance with the specifications of the system manufacturer. Examples of sampling requirements applicable for a spherical scanning system employing field reconstruction is provided in B.4.3.3.2. RF field strength or power density shall be measured or reconstructed in a number of points allowing for spatial averaging in accordance with B.3.3. If the compliance boundary is determined without applying spatial averaging, the spatial resolution of RF field strength or power density (measured directly or reconstructed) shall be good enough to resolve the peak value in the direction of interest with respect to the EUT (e.g. front, back, side, and above/below).

B.4.3.3 Methods based on field reconstruction at the evaluation points

B.4.3.3.1 General

RF field strength or power density shall be reconstructed at the evaluation points based on techniques to transform the fields back or forward. Measurements of field amplitude, phase and polarization shall be made at points on a surface surrounding the EUT. This establishes the parameters to model a set of isotropic sources on the surface that is producing the same field as the EUT at the evaluation location. The scanned surface shall contain all the relevant energy that is radiated from the EUT. The parameters of this set of isotropic radiators are then used to calculate the field or power density at the evaluation points.

A summary of the main steps is given in Figure B.11.

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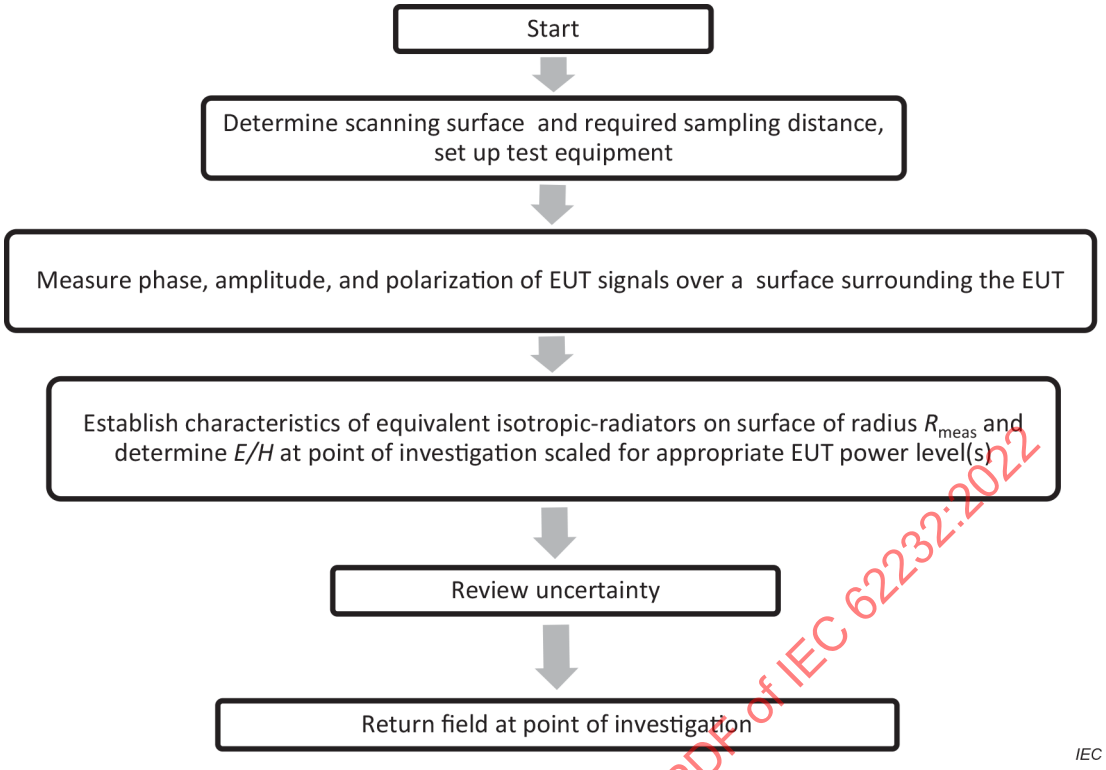


Figure B.11 – Outline of the surface scanning methodology

Methods to perform surface scanning could be, but are not limited to, far-field, compact range, planar, cylindrical, or spherical near-field provided the methodology is accurately described and the uncertainty is quantified. For simplicity, the specifications in B.4.3.3 are provided assuming a spherical measurement surface. Generalizations to other measurement surfaces are possible. IEC/IEEE 63195-1 as well as IEEE Std 1720™-2012 [74] provide information and requirements for planar and cylindrical scanning.

B.4.3.3.2 Measurement equipment and test environment

B.4.3.3.2.1 General description

The surface scanning consists of an EUT mounted on an azimuthal positioner and the probe(s) mounted on a support structure at distance R_{meas} from the EUT. This method generally requires the ability to measure the phase of the signal. Alternatively, field reconstruction algorithms such as those described in IEC/IEEE 63195-1 shall be used to derive the phase from amplitude only measurements. Detection shall consist of either one probe moved mechanically along the structure, or one probe array switched electronically in order to perform an angular elevation scan of the electromagnetic fields. Alternatively, the EUT can be moved to different elevation angles by means of an additional elevation positioner.

An example of an antenna measurement system is provided in Figure B.12 which includes the following equipment:

a) anechoic chamber, or semi-anechoic chamber, or suitable test site;
b) probe(s) (antenna(s));
c) support structure for probe(s);
d) supporting structure for the EUT;
e) vector-receiver;
f) synthesizer and amplifier(s);
g) probe positioning system or probe array controller system;

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h) EUT positioning system.

The computer controlling the measurement equipment shall be placed so as not to influence the measurements. The test shall be performed using probe antennas providing electric or magnetic field measurements. The probe antennas shall be accurately positioned to measure the field distribution in a spherical surface around the EUT. The measurement shall be carried out with a minimum of reflections from the environment in order to simulate free space conditions. For measurement systems which do not make use of a reference antenna to acquire phase information, a vector network analyser is needed to generate the source signal as well as serving as the receiver.

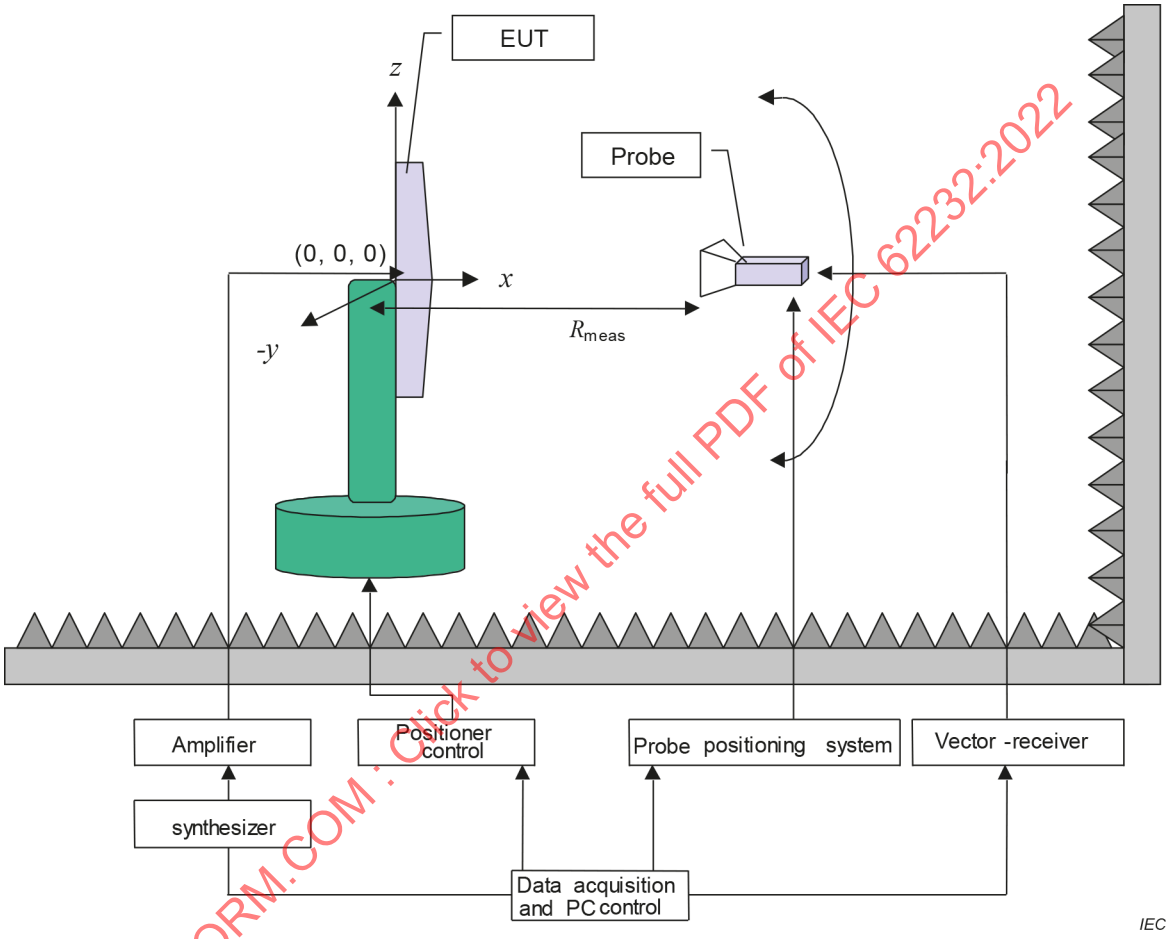


Figure B.12 – Block diagram of the antenna measurement system

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B.4.3.3.2.2 Positioning, orientation, and sampling requirements of the scanning equipment

The measurement system shall be able to scan a spherical surface of radius R_{meas} with radial accuracy within 10 % of the minimum distance between the measurement point and the closest point to the EUT and not more than 50 % of the wavelength. The angular position accuracy shall be of 0,5°.

The distance between the EUT reference point at the origin of rotation and the measurement probe(s) shall be the greater of the distance required such that the probes and measurement equipment are operating within their calibrated level range for the power specifications of the EUT, see Figure B.13.

The sampling criterion requires a maximum angular spacing of the measurement points of $\lambda/2$ over the sphere circumscribing the EUT with radius R_{min}. The angles $\delta\varphi$ (azimuth) and $\delta\theta$ (elevation) between adjacent measurements shall comply with the constraints of Figure B.14.

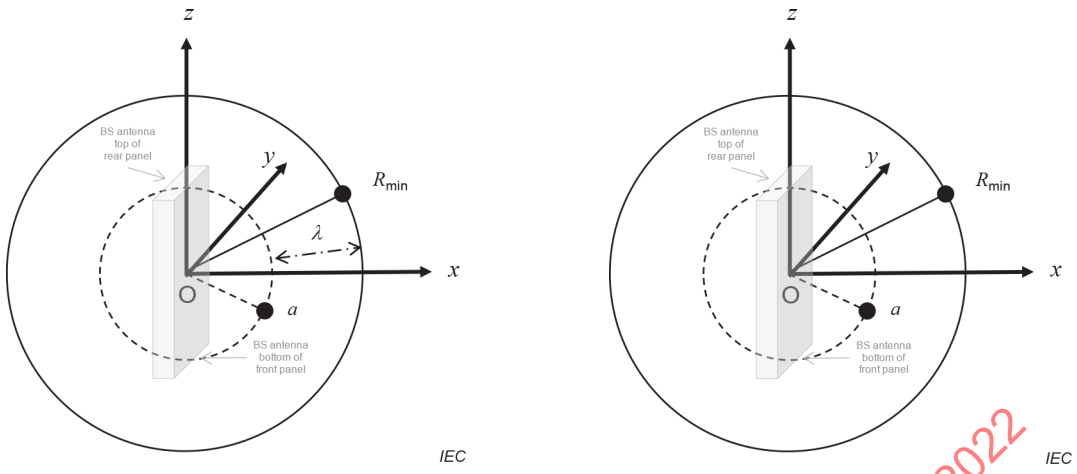
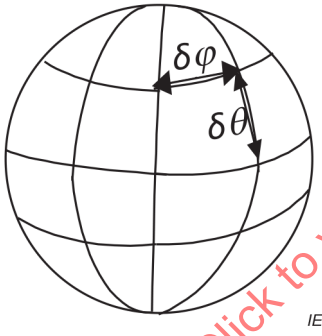


Figure B.13 – Minimum radius constraint, where a denotes the minimum radius of a sphere, centred at the reference point, that encompasses the EUT



$$\delta\varphi \leq \frac{\lambda}{2 \times R_{meas}}$$

$$\delta\theta \leq \frac{\lambda}{2 \times R_{meas}}$$

Figure B.14 – Maximum angular sampling spacing constraint

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B.4.3.3.2.3 Measurement probe

The probe or probe array shall be designed and dimensioned such as not to disturb the electromagnetic fields generated by the EUT. The probe(s) gain shall be calibrated with a measurement uncertainty less than ±1,0 dB. The probe shall be able to provide orthogonal polarization with cross-polar isolation better than 30 dB. Alternatively, a second scan with a probe rotated by 90° could detect the cross-polar values.

B.4.3.3.2.4 Supporting structure of the EUT

The antenna shall be mounted on a dielectric holder fixed on the positioning system. The holder shall be made of low conductivity and low relative permittivity material(s): $\tan \delta \leq 0{,}05$ and $\varepsilon_r \leq 1{,}2$.

Alternatively, the antenna can be mounted on a metallic mast, if this is the normal operating situation of the antenna. If the mounting situation differs from a free-space equivalent, this shall be documented in the measurement results.

The antenna shall be mounted so that the reference point (0, 0, 0) is in the centre of the sphere.

B.4.3.3.2.5 Test site

The level of perturbation due to reflections and/or noise shall not exceed −17 dB of the applicable RF field strength or power density limit for any measurement. Additional information is provided in B.4.3.4.2.5. Ambient temperature shall be in the range of 10 °C to 30 °C and shall not vary by more than ±5 °C during the test.

B.4.3.3.3 Measurement protocol

a) Basic test configuration

The basic test configuration corresponds to an initial angle $\varphi = \varphi_0$ (azimuth). The angular scan θ (elevation) shall start at one of the edges of the circular path and be incremented by a value $\delta\theta$. The angular scan in elevation shall be performed along the whole circular path. At each $\theta_i = \theta_{i-1} + \delta\theta$ position of the probe(s), the received or emitted signal shall be recorded. The basic test configuration should be repeated for each azimuthal increment $\delta\varphi$.

b) Pre-test procedure

Check if the detection probe(s) can accept the power levels radiated during the measurements. Calibrate the electric and/or magnetic probe(s) in gain. Alternatively, confirm that the absolute values of the electromagnetic fields can be derived from the measurement data over the whole sphere.

At the frequency or frequencies used for measurements determine values of $\delta\varphi$, φ_{max}, $\delta\theta$, θ_{min}, θ_{max}, R_{meas} where

$\delta\varphi$ is the azimuthal increment;

φ_{max} is the maximum azimuth angle value;

$\delta\theta$ is the elevation increment;

θ_{min} is the lower edge angle of the circular elevation path;

θ_{max} is the upper edge angle of the circular elevation path;

R_{meas} is the radius of the scan in elevation.

Confirm that the total contribution of interferences and reflected signals is less than −17 dB below the incident signal.

c) Test procedure

1) Confirm proper operation of the probe(s), measurement system and equipment.
2) Mount the EUT in the measurement configuration.
3) Configure the EUT for optimum output power, at the desired frequency and for the desired operating modes.
4) Position (or configure) the probe(s) at the initial evaluation location.
5) Perform an initial elevation scan at the reference azimuth position and store the data.
6) Measure and acquire the electromagnetic fields distribution.
7) The EUT or the probe(s) are moved incrementally in azimuth with $\Delta\varphi$ angle step around a vertical axis that corresponds also to a symmetry axis for the sphere to be scanned.
8) Repeat the electromagnetic fields measurement until $\varphi_i = \varphi_{max}$ (with $\varphi_i = \varphi_{i-1} + \delta\varphi$, with $i_{min} = 1$).
9) After measurements, perform again a final elevation scan at the reference azimuth position and compare the data with the initial elevation scan. Verify that the final values at the maximum levels are within 5 % of the initial values (influence of the drift due to surrounding equipment and environment).
10) If the drift is greater than 5 % of power density or square of RF field strength (either positive or negative), it shall be considered as a systematic offset rather than an uncertainty. The reconstructed RF field strength or power density shall therefore be compensated adding the absolute drift value.

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B.4.3.3.4 Post-processing

B.4.3.3.4.1 General

The electromagnetic field values shall be obtained by applying a post-processing technique on the set of measured data. Power density is determined from the calculation of the Poynting vector or by plane-wave equivalent approximation in accordance with B.4.3.2.1.

B.4.3.3.4.2 Determining electromagnetic field values outside or inside the scanned surface

The measured tangential electromagnetic field shall be mapped on a spherical vector-wave expansion consisting of a sum of TE and TM wave functions. The number of modes to consider in the expansion shall be at least $N = \frac{2\pi}{\lambda} a + 10$. Modes of higher order are evanescent and have no significant contribution for distances larger than R_{min}. Therefore, a zone of exclusion exists in the vicinity of the antenna where the expansion cannot be performed. This corresponds to the region with significant contributions from reactive field components.

B.4.3.3.4.3 Scaling measurements to a given input power

The measured electric and magnetic fields, denoted E_{o} and H_{o}, respectively, are obtained for a given input power P_{o}. As the fields are proportional to the square root of the input power, the RF field strength levels at the desired transmitted power P shall be obtained from Equation (B.20):

$$E = E_{\text{o}} \cdot \sqrt{\frac{P}{P_{\text{o}}}} \quad \text{or} \quad H = H_{\text{o}} \cdot \sqrt{\frac{P}{P_{\text{o}}}} \tag{B.20}$$

B.4.3.4 Measurements based on direct measurements at the evaluation points

B.4.3.4.1 General

Direct measurements of electric fields, magnetic fields and power density shall be made within a volume or at a surface corresponding to the evaluation points. Within source region I (A.1.3), the amplitude and phase of the field shall be measured to evaluate power density. Alternatively, phase retrieval algorithms such as those described in IEC/IEEE 63195-1 shall be used to retrieve the phase from amplitude only measurements. A summary of the main steps is given in Figure B.15.

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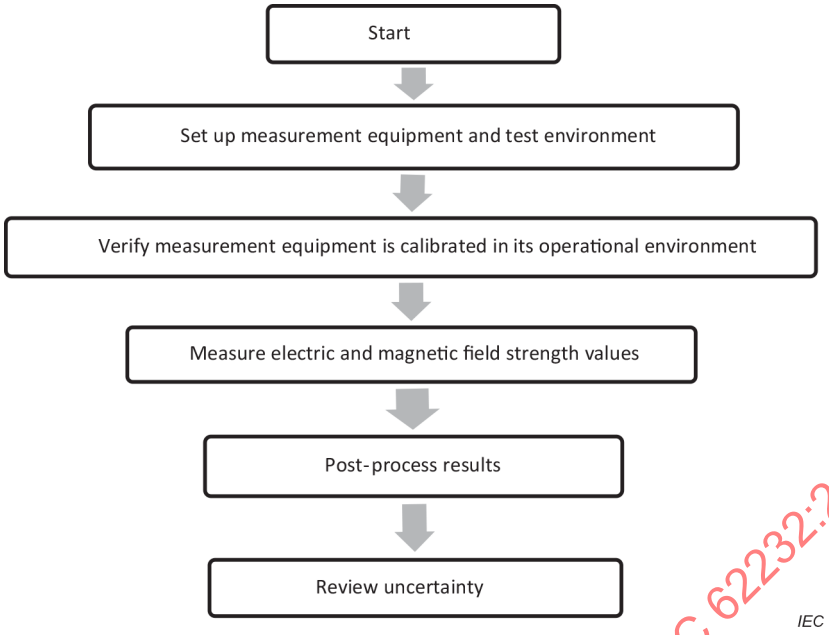


Figure B.15 – Outline of the volume/surface scanning methodology

B.4.3.4.2 Measurement equipment and test environment

B.4.3.4.2.1 General description

The volume/surface scanning equipment consists of an isotropic probe and a structure to hold the EUT and the probe allowing a 3D movement relative to each other.

The following equipment should be used:

a) anechoic chamber or suitable test site;
b) electric and/or magnetic isotropic probe;
c) supporting structure for isotropic probe;
d) supporting structure for the EUT;
e) synthesizer and amplifier(s);
f) isotropic probe positioning system or probe array controller system;
g) EUT positioning system;
h) receiver or other measurement equipment.

A computer is generally used to control the measurement equipment. The test equipment shall be placed so as not to influence the measurements. A typical near-field EUT measurement system configuration is shown in Figure B.16.

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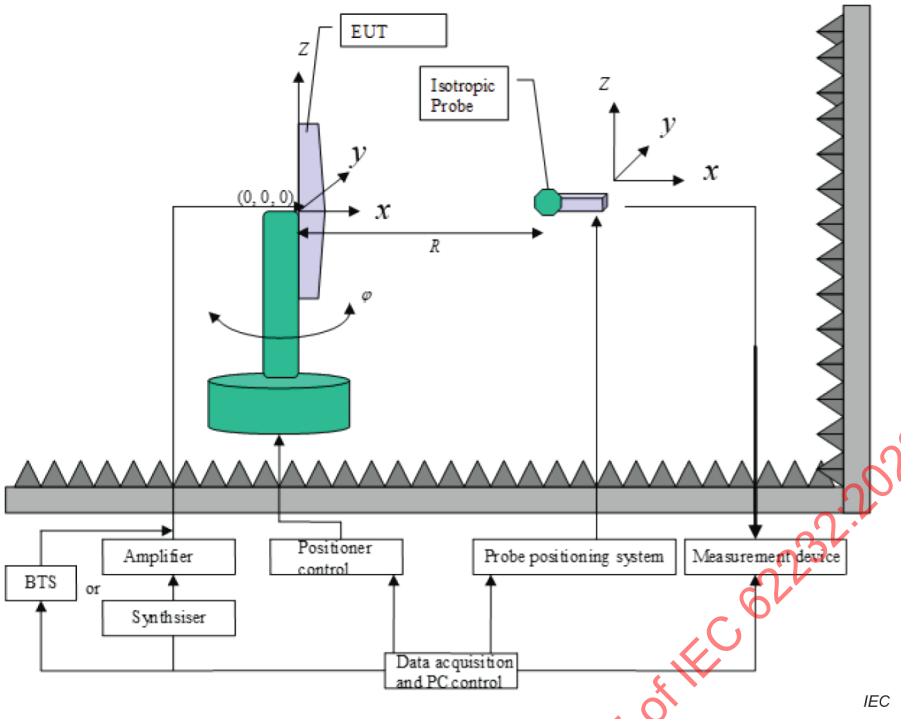


Figure B.16 – Block diagram of typical near-field EUT measurement system

B.4.3.4.2.2 Scanning equipment

The positioning system holding the EUT and the isotropic probe shall be able to scan a specified volume/surface of the test environment. The sampling of the specified volume/surface is achieved through the relative displacements, translation, and rotation, between the structure supporting the probe and the EUT. The measurements shall be carried out as a set of scans on cylindrical, spherical, or planar surfaces.

The accuracy of the probe tip positioning over the measurement area shall be less than or equal to ±0,5 cm. The resolution at which the measurement system is able to sample the RF field strengths shall be $\lambda/2$ or less. Cylindrical, Cartesian, or spherical coordinate systems can be used as illustrated in B.2.1.

B.4.3.4.2.3 Measurement equipment

The measurement equipment shall be composed of the isotropic probe and the measurement device. The isotropic probe shall be designed and dimensioned such as not to disturb the electromagnetic fields generated by the EUT. The measurement equipment shall have a measurement range compatible with the RF power levels used in the test and the resulting fields at the evaluation location.

Where E-field strength measurement equipment is used, the lower detection limit shall be lower than 3 V m^{-1} and the upper detection limit shall be higher than 200 V m^{-1}. Where H-field strength measurement equipment is used, the lower detection limit shall be lower than 0,03 A m^{-1} and the upper detection limit shall be higher than 0,6 A m^{-1}.

B.4.3.4.2.4 Supporting structure for the EUT

The antenna shall be mounted on a dielectric holder fixed on the positioning system. The holder shall be made of low conductivity and low relative permittivity material(s): $\tan \delta \leq 0{,}05$ and $\varepsilon_r \leq 1{,}2$.

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Alternatively, the antenna can be mounted at a metallic support, if this is the normal operating situation of the antenna. If the mounting situation differs from a free-space equivalent, this shall be documented in the measurement results.

B.4.3.4.2.5 Test site

The test site shall be evaluated in order to minimize the level of perturbation due to reflections or ambient noise which shall not exceed −17 dB of the incident field at any evaluation location.

This can be achieved using an anechoic chamber (shielded room covered inside by absorbing material). If an outdoor measurement system is used, ground reflections can be reduced by elevation the probe and the EUT above the ground, using impermeable absorbers, ferrites or diffraction fence. Absorbing materials can be placed in the direction of the main reflection area [75], [76]. Noise ratio can be reduced by avoiding external source frequencies or making tests with higher signal levels or filtering.

Ambient temperature shall be in the range of 10 °C to 30 °C and shall not vary by more than ±5 °C during the test.

B.4.3.4.3 Measurement protocol

a) Mount the EUT in the measurement configuration.

b) Configure the EUT for optimum output power, at the desired frequency and for the desired operating modes.

c) Perform an initial E-field strength or H-field strength measurement at the reference position P_r close to the antenna (but at a distance larger than $\lambda/2$) and store the data for the power drift check.

d) Perform 3D scanning around the EUT, in accordance with the general requirements to acquire the electromagnetic fields distribution.

e) As a final step in the test, repeat the E-field strength or H-field strength measurement at the reference position P_r. If the field value deviates more than 5 % from the initial values then the power chain shall be checked, and the test repeated.

B.4.3.4.4 Post-processing

E-field strength and H-field strength at evaluation points are obtained directly from the measurement and/or by interpolation between measurement points. Power density is determined from the calculation of the Poynting vector or by plane-wave equivalent approximation in accordance with B.4.3.2.1.

B.4.3.5 System performance check

The measurement system shall be validated by performing measurements on a calibrated reference antenna, e.g. a half-wave dipole, in accordance with the procedures described in B.4.3.3 and B.4.3.4. Electric field strength or magnetic field strength (depending on the probe) shall be compared in the far-field to the reference field given by the far-field Equation (B.21):

$$E = \frac{\sqrt{30 \times P \cdot G}}{r} \quad \text{or} \quad H = \frac{E}{\eta_0} = \frac{\sqrt{P \cdot G}}{69 \times r} \tag{B.21}$$

where

P is the input power of the reference antenna, in watts;

G is the gain in the main beam of the reference antenna;

r is the distance between the probe and the reference antenna, in metres;

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η_0 is the free space impedance.

The error on the performance checking shall be below ±1 dB.

B.4.4 RF field strength and power density measurement uncertainty

B.4.4.1 In-situ RF measurement uncertainty

Guidance on uncertainty is applicable to both RF field strength and power density measurements. The sources of uncertainty identified in Table B.7 or Table B.8 shall be considered in three categories:

a) measurement equipment;

b) measurement methodology; and

c) source and environment.

The measurement equipment uncertainty shall be in accordance with performance requirements in Table B.5 and Table B.6. A description of relevant influence quantities and how to assess the corresponding uncertainty is given in Clause G.7.

The measurement methodology uncertainty shall be quantified.

See uncertainty requirements in 6.3 and Clause 9.

Where practical, the uncertainty of the source and environment factors (e.g. rain, open windows, environmental clutter) should be quantified. If source and environment factors are difficult to quantify, they shall at least be described in the report, see Clause 10.

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Table B.7 – Example template for estimating the expanded uncertainty of an in-situ RF field strength measurement that used a frequency selective equipment

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact. CF	$c^2 \cdot u^2$
Measurement equipment								
Calibration of the meter (or spectrum analyser)	dB	normal		1,96	1			
Calibration of the antenna factor	dB	normal		1,96	1			
Calibration of the cable attenuation	dB	normal		1,96	1			
Combined frequency response of the meter/cable/antenna	dB	rect.		√3	1			
Combined linearity deviation of the meter/cable/antenna	dB	rect.		√3	1			
Isotropy of the antenna	dB	rect.		√3	1			
Combined temperature and humidity response of meter/cable/antenna	dB	rect.		√3	1			
Mismatch between antenna and meter/ spectrum analyser	dB	U-shape		√2	1			
Methodology								
Probe position in high field gradients	dB	rect.		√3	1			
Field scattering from surveyor's body	dB	rect.		√3	1			
Mutual coupling between measurement antenna or isotropic probe and object	dB	rect.		√3	1			
Meter reading error of fluctuating signals	dB	triang.		√6	1			
Source and environment								
Variation in the power of the RF source from the nominal level	dB	rect.		√3	1			
Field reflections from movable large objects near the source during measurement	dB	rect.		√3	1			
Scattering from nearby objects and the ground	dB	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} (c_i^2 \cdot u_i^2)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								

NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence.

NOTE 2 See Annex E for guidance on the variables in this table.

NOTE 3 This table is under the assumption that the logarithmic expression of the measured quantities can be similarly treated to that of the linear expression in view of statistical properties.

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Table B.8 – Example template for estimating the expanded uncertainty of an in-situ RF field strength measurement that used a broadband equipment

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact CF	$c^2 \cdot u^2$
Measurement equipment								
Calibration of field probe	dB	normal		1,96	1			
Frequency response of field probe	dB	rect.		√3	1			
Isotropy of the field probe	dB	rect.		√3	1			
Temperature response of the field probe	dB	rect.		√3	1			
Linearity deviation of the field probe	dB	rect.		√3	1			
Methodology								
Meter reading error of fluctuating signals	dB	triang.		√6	1			
Field reflections from surveyor's body	dB	rect.		√3	1			
Probe position in high field gradients	dB	rect.		√3	1			
Mutual coupling between measurement antenna or isotropic probe and object	dB	rect.		√3	1			
Source and environment								
Variation in the power of the RF source from the nominal level	dB	rect.		√3	1			
Scattering from nearby objects and the ground	dB	rect.		√3	1			
Field reflections from movable large objects near the source	dB	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} (c_i^2 \cdot u_i^2)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								

NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence.

NOTE 2 See Annex E for guidance on the variables in this table.

NOTE 3 This table is under the assumption that the logarithmic expression of the measured quantities can be similarly treated to that of the linear expression in view of statistical properties.

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B.4.4.2 Laboratory measurement uncertainty

B.4.4.2.1 Uncertainty for the surface scanning method

The sources of uncertainty identified in Table B.9 shall be considered in four categories: measurement equipment, mechanical constraints, physical parameters, and post-processing. A description of relevant influence quantities and how to assess the corresponding uncertainty is given in Annex G. Additional guidelines are provided in IEC/IEEE 63195-1.

After post-processing, the expanded uncertainty shall not exceed 30 %.

Table B.9 – Example template for estimating the expanded uncertainty of a laboratory-based RF field strength or power density measurement using the surface scanning method

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact. CF	$c^2 \cdot u^2$
Measurement equipment								
Calibration of field probe	%	normal		1,96	1			
Isotropy of field probe	%	rect.		√3	1			
Linearity deviation of the field probe	%	rect.		√3	1			
Measurement device	%	normal		1,96	1			
Noise	%	normal		1,96	1			
Integration time	%	normal		1,96	1			
Power chain	%	normal		1,96	1			
Mechanical constraints								
Positioning system	%	rect.		√3	1			
Matching between probe and EUT	%	rect.		√3	1			
Physical parameters								
Drifts in output power of the EUT, temperature and humidity	%	rect.		√3	1			
Perturbation by the environment	%	rect.		√3	1			
Post-processing								
Contribution of post-processing	%	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} \left(c_i^2 \cdot u_i^2 \right)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								
NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence. NOTE 2 See Annex E for guidance on the variables in this table.								

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B.4.4.2.2 Uncertainty for surface or volume scans

The sources of uncertainty identified in Table B.10 shall be considered in three categories: measurement equipment, mechanical constraints, and physical parameters. A description of relevant influence quantities and how to assess the corresponding uncertainty is given in Annex G. Additional guidelines are provided in IEC/IEEE 63195-1.

After post-processing, the expanded uncertainty shall not exceed 30 %.

Table B.10 – Example template for estimating the expanded uncertainty of a laboratory-based RF field strength or power density measurement using the volume scanning method

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact. CF	$c^2 \cdot u^2$
Measurement equipment								
Calibration of field probe	%	normal		1,96	1			
Isotropy of field probe	%	rect.		√3	1			
Linearity deviation of the field probe	%	rect.		√3	1			
Fields out of measurement range	%	rect.		√3	1			
Measurement device	%	normal		1,96	1			
Noise	%	normal		1,96	1			
Integration time	%	normal		1,96	1			
Power chain	%	normal		1,96	1			
Mechanical constraints								
Positioning system	%	rect.		√3	1			
Matching between probe and EUT	%	rect.		√3	1			
Physical parameters								
Drifts in output power of the EUT, temperature and humidity	%	rect.		√3	1			
Perturbation by the environment	%	rect.		√3	1			
Post-processing								
Contribution of post-processing	%	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} \left(c_i^2 \cdot u_i^2 \right)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								
NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence. NOTE 2 See Annex E for guidance on the variables in this table.								

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B.5 SAR measurements

B.5.1 Overview of SAR measurements

The methods described in B.5.2 to B.5.4 are applicable for both maximum peak spatial-average SAR (psSAR) and whole-body average SAR. They are based on and make reference to IEC/IEEE 62209-1528 and IEC 62209-3.

B.5.2 SAR measurement requirements

B.5.2.1 General requirements

The SAR measurement system is composed of a flat phantom shell filled with tissue-equivalent medium, an EUT holder, one or multiple scalar probes and/or vector probes and electronic measurement equipment. The SAR measurement system can be a scanning system or an array system. General specifications and requirements on all of these components as well as on the measurement environment as specified in IEC/IEEE 62209-1528 or IEC 62209-3 shall be used.

B.5.2.2 Phantom selection

B.5.2.2.1 General

Three different phantoms can be used for SAR measurements, see Figure B.17:

a) a flat elliptical phantom as specified in IEC/IEEE 62209-1528;

b) a flat box-shaped phantom with lateral dimensions of 1,54 m × 0,339 m [61], [77]. In this document, this phantom is referred to as the large box-shaped phantom;

c) a flat box-shaped phantom with lateral dimensions of 0,96 m × 0,233 m [72]. In this document, this phantom is referred to as the small box-shaped phantom.

For maximum peak spatial-average SAR (psSAR) measurements, all three phantoms specified above can be used.

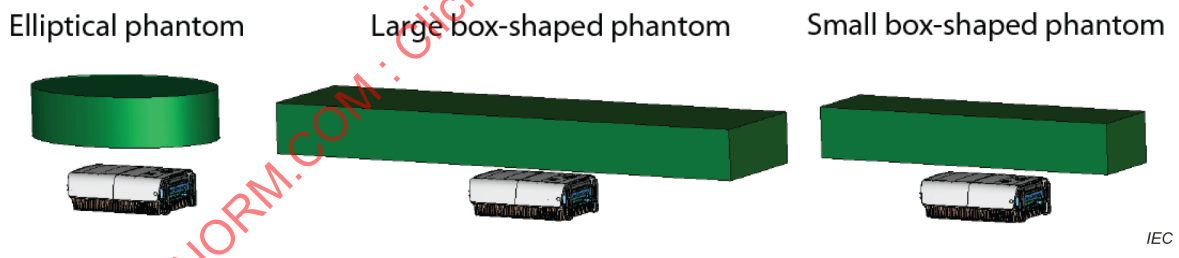


Figure B.17 – Examples of positioning of the EUT relative to the relevant phantom

For whole-body SAR measurements related to occupational exposure, the large box-shaped phantom shall be the preferred choice. However, the small box-shaped phantom and the elliptical phantom can be used to determine the absorbed power if the broadside of the EUT can be circumscribed by the lateral dimensions of the phantoms. In addition, the uncertainty introduced, compared with using the preferred phantom, shall be assessed. For this case the absorbed power shall be normalized with the mass of an adult in accordance with 8.2.3 and B.5.3.4.

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When general public exposure is considered, it is necessary to distinguish between two possible exposure configurations.

- For products that are placed arbitrarily in homes, offices and other places, the exposure evaluations shall be performed assuming potential exposure of all members of the general public, including children. The small box-shaped phantom should be chosen, but measurements in a small volume of the large phantom can also be used if the obtained measurement results are corrected as specified in B.5.3.4. However, the flat elliptical phantom can be used to determine the absorbed power if the broadside of the EUT is circumscribed by the ellipse and if the uncertainty introduced (compared with using the preferred phantom) is assessed. For this case the absorbed power shall be normalized with the mass of a child in accordance with 8.2.3 and B.5.3.4.
- For products which are installed in ways preventing children from entering the immediate vicinity of the transmitting antenna(s), the evaluations can be performed assuming adult exposure. For this case the large box-shaped phantom should be chosen. However, the small box-shaped phantom and the elliptical phantom can be used to determine the absorbed power if the broadside of the EUT is circumscribed by the lateral dimensions of the phantoms and if the uncertainty introduced (compared with using the preferred phantom) is assessed. The absorbed power shall be normalized with the mass of an adult in accordance with 8.2.3 and B.5.3.4.

The phantom shell thickness of the side facing the EUT shall be 2,0 mm with a tolerance of ±0,2 mm as specified in IEC/IEEE 62209-1528 and IEC 62209-3; however, external strengthening fins of a maximum height (thickness) of 3 mm can be used provided that the effect on the local SAR is less than 5 %. When the phantom is filled with tissue-equivalent medium at the required depth, the sagging shall be less than 2 mm from true flat.

NOTE The effect of strengthening fins on local SAR is something that is verified by the phantom manufacturer. One way to do this is to compare the result obtained with external strengthening fins with results obtained using the elliptical flat phantom in IEC/IEEE 62209-1528 or IEC 62209-3. Another way is to use simulations using generic dipole sources to assess the effect in the near-field and the plane wave incidence to address effects for far-field exposure.

The depth of the tissue-equivalent medium during the measurements shall be at least 0,15 m from the shell-medium interface. In accordance with IEC/IEEE 62209-1528, medium depth of less than 0,15 m can be used only if it is demonstrated (e.g. using numerical simulations) that the effect on peak spatial average SAR is less than 1 % under all conditions. If it is more than 1 % but less than 3 %, uncertainty for the maximum value from the demonstration shall be added to the uncertainty budget.

B.5.2.2.2 EUT configuration for SAR measurement

If the EUT is a BS with integrated antenna(s), it shall use its internal transmitter, the normal power supply, and the original antenna(s). The BS shall be configured in accordance with the specifications provided by the manufacturer, and the output power and frequency (channel) shall be controlled using an internal test programme or by appropriate external equipment.

If the BS is intended for use with external antenna(s), the same requirements apply, but the BS can be replaced with any transmitter providing the same antenna input power and frequency as the BS under evaluation.

The appropriate operating modes of the EUT (e.g. modulation, source coding, channel bandwidth, etc.) shall be selected for testing taking into consideration different output power levels, such that the maximum SAR is assessed. When standardized conformance test models exist (e.g. 3GPP E-TM 3.1 for LTE) these shall be used for testing and the test model corresponding to the maximum RF output power condition shall be selected. If the EUT is tested in a lower power configuration, scaling shall be performed to obtain SAR corresponding to the maximum output power level. A continuous wave (CW) signal can be used provided that the average power is adjusted to produce a conservative result.

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SAR shall be measured at the centre frequency. If the width of the transmit frequency band for the EUT exceeds 5 % of the centre frequency, measurements at the lower and upper frequencies shall also be performed. If the EUT can operate with different channel bandwidths, the bandwidth leading to the maximum transmitted power shall be selected. If the EUT is tested in a lower power configuration, scaling to the maximum power shall be performed. If the EUT can be configured to transmit in the entire transmit band, separate measurements for low, mid and high frequencies are not required.

B.5.2.2.3 SAR measurement requirements

The following requirements shall be addressed.

a) Maximum peak spatial-average SAR (psSAR) and/or whole-body SAR shall be considered.

b) If the EUT is capable of simultaneous transmission (multiple bands, multiple technologies, MIMO, etc.), contributions shall be evaluated and combined using the formulas specified in 8.5 and taking into consideration IEC/IEEE 62209-1528 and IEC 62209-3. For MIMO antennas emitting correlated waveforms and for a test separation distance less than 5 cm and with the distance between adjacent antennas larger than half a free-space wavelength, the SAR distributions from adjacent antennas have little or no overlap and the varied phase of excitation has little impact on the maximum peak spatial-average SAR (psSAR). In such case, the combined exposure should be evaluated by selection of the highest assessed maximum standalone SAR value or by exciting all antennas simultaneously considering a fixed phase combination [78].

c) To determine the maximum SAR, the evaluation shall be performed with the antenna, or the side of the EUT where the antenna is located, facing the phantom. The antenna or EUT shall be positioned so as to obtain the highest possible SAR, which for many situations implies that the antenna's main lobe direction shall be orthogonal to the phantom surface, see examples in Figure B.17. For whole-body RF exposure, it can be necessary to align the phantom with the antenna in the same relationship/orientation as in the actual installation to account for proper RF coupling.

d) For local SAR measurements, small adjustments of the EUT position can be made in order to avoid that an antenna element is positioned close to an edge of the phantom. The EUT positioning shall be documented in the test report. If the EUT is equal to or larger than the measurement area supported by the phantom, the EUT shall be shifted based on IEC/IEEE 62209-1528 or IEC 62209-3 such that multiple scans can be combined to encompass at least the projection of the EUT over the flat phantom.

e) To establish the compliance boundary, testing shall be performed at different separation distances up to 1 000 mm from the phantom to determine the compliance distance, i.e. the distance at which the SAR value is below the appropriate SAR limit for the assessment configuration. Measurements in a number of positions can be necessary, see guidance on compliance boundary assessment in 6.1.2.

Compliance boundaries for different power levels can be obtained by linear scaling of a SAR versus separation distance curve, see 6.1.5.3.

B.5.3 SAR measurement description

B.5.3.1 General method

The SAR assessment protocol described below is applicable to both local SAR, see B.5.3.3, and whole-body SAR, see B.5.3.4.

a) Step 1: For each transmitter and transmit band used by the EUT, measure at least the centre frequency at zero distance between the EUT antenna and the phantom shell.

b) Step 2: For each transmitter and transmit band used by the EUT, the frequency that provides the highest SAR value shall be used to measure the SAR at additional separation distances until the SAR is below the exposure limit; the maximum separation distance to be used for tests shall take into account the combined SAR, see B.5.2.2.3 b).

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c) Step 3: Establish the separation distance at which the combined SAR is below the exposure limit, see B.5.2.2.3 b).

d) Step 4: Position the EUT antenna at the established separation distance and measure SAR for lower, centre and upper frequency of each band in order to verify that the combined SAR is below the exposure limit based on B.5.2.2.3 b). If necessary, repeat at larger separation distances until the measured value is below the applicable SAR limits. When SAR assessment is performed on multiple surfaces of the EUT/antenna, these measurements shall be made on all surfaces required in 7.2.4.1 of IEC/IEEE 62209-1528:2020 or 7.1.7 of IEC 62209-3:2019 at the centre frequency (default) or the frequency with highest transmitted power (if measured). Measurements on the remaining two frequencies are performed only on the surface with highest SAR among all measured surfaces. If the bandwidth of a transmit frequency band does not exceed 5 % of its centre frequency, measurements at the lower and upper frequencies are not required.

IEC/IEEE 62209-1528 and IEC 62209-3 specify local SAR measurement procedures for wireless communication devices (EUT) used in close proximity to the human body. Therefore, IEC/IEEE 62209-1528 and IEC 62209-3 are not relevant in their entirety for the local and whole-body SAR measurements relating to base stations. General specifications concerning measurement preparation are applicable for both local and whole-body SAR measurements with one exception. It is only for local SAR that a correction of the measured result is required due to deviations of complex permittivity from the target values. Whole-body SAR has been found to be less sensitive to this deviation [79], and as a consequence, the effect shall instead be included in the uncertainty budget, see G.9.5. Parts of the fast SAR evaluations, measurement procedure, and post-processing are only applicable for local SAR assessments (evident from its context).

B.5.3.2 System check and system validation

System check shall be performed using reference dipoles in accordance with 7.2.1 and A.2 of IEC/IEEE 62209-1528:2020, taking into account the numerical reference SAR values listed in columns 3, 4, 5 and 6 of Table B.11, which is extracted from IEC/IEEE 62209-1528:2020, Table 23. Alternatively, system check shall be performed using reference antennas in accordance with 7.1.3 and D.3 of IEC 62209-3:2019.

The system check shall be performed using the same tissue-equivalent medium as in the compliance test and at a chosen fixed frequency that is within ±10 % or ±100 MHz of the compliance test mid-band frequency, whichever is greater. The system check is successful if it satisfies the criteria specified in A.2.5 of IEC/IEEE 62209-1528:2020 or D.3.4 of IEC 62209-3:2019.

System validation shall be performed using reference dipoles in accordance with A.3 of IEC/IEEE 62209-1528:2020 or D.4 of IEC 62209-3:2019, taking into account the numerical reference SAR values listed in columns 3, 4, and 7 of Table B.11. The difference between the measured values and the target values given in Table B.11 shall be less than the expanded uncertainty for the system validation using the template described in Table B.15 for whole-body SAR system validation.

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Table B.11 – Numerical reference SAR values for reference dipoles and flat phantom – All values are normalized to a forward power of 1 W

Frequency	Phantom shell thickness	1 g SAR	10 g SAR	Local SAR at surface (above feedpoint)	Local SAR at surface (y = 2 cm offset from feedpoint)	Whole-body SAR[a,b]
MHz	mm	W kg^{-1}	W kg^{-1}	W kg^{-1}	W kg^{-1}	W kg^{-1}
300	2,0	2,85	1,94	4,14	2,00	0,073 / 0,021 / 0,073
450	2,0	4,58	3,06	6,75	2,98	0,073 / 0,021 / 0,074
750	2,0	8,49	5,55	12,6	4,59	0,070 / 0,020 / 0,070
835	2,0	9,56	6,22	14,1	4,90	0,069 / 0,019 / 0,068
900	2,0	10,9	6,99	16,4	5,40	0,068 / 0,019 / 0,068
1 450	2,0	29,0	16,0	50,2	6,50	0,068 / 0,019 / 0,068
1 800	2,0	38,4	20,1	69,5	6,80	0,064 / 0,017 / 0,064
1 900	2,0	39,7	20,5	72,1	6,60	0,062 / 0,017 / 0,062
1 950	2,0	40,5	20,9	72,7	6,60	0,062 / 0,017 / 0,062
2 000	2,0	41,1	21,1	74,6	6,50	0,061 / 0,017 / 0,061
2 450	2,0	52,4	24,0	104	7,70	0,055 / 0,015 / 0,055
2 585	2,0	55,9	24,4	119	7,90	0,052 / 0,014 / 0,052
2 600	2,0	55,3	24,6	113	8,29	0,052 / 0,014 / 0,052
3 000	2,0	63,8	25,7	140	9,50	0,046 / 0,013 / 0,046
3 500	2,0	67,1	25,0	169	12,1	0,039 / 0,011 / 0,040
3 700	2,0	67,4	24,2	178	12,7	0,038 / 0,010 / 0,038
5 000	2,0	77,9	22,1	305	15,1	0,028 / 0,008 / 0,028
5 200	2,0	76,5	21,6	310	15,9	0,027 / 0,007 / 0,027
5 500	2,0	83,3	23,4	349	18,1	0,025 / 0,007 / 0,025
5 800	2,0	78,0	21,9	341	20,3	0,024 / 0,007 / 0,024

The mechanical dimensions of the reference dipoles given in IEC/IEEE 62209-1528 shall be used. The values above 3 GHz depend on the dipole spacer and detailed construction of the dipoles and can vary by as much as ±10 %. The reasons are that the dipole dimensions are short with respect to arm diameter and spacer dimensions, i.e. the numerical reference values are not generic and need to be determined for a particular configuration.

The phantom dimensions given in B.5.2.2 shall be used. The values above 3 GHz depend on the dipole spacer and can vary by as much as ±10 %.

If the dipole forward power results in measured SAR values that are above the dynamic range of the probe, lower powers can be used so as not to introduce additional measurement uncertainty or damage the probe.

[a] Values are given as follows: small box-shaped phantom / large box-shaped phantom / elliptical phantom.

[b] Whole-body SAR numerical reference values listed in column 7 were obtained with the dipole oriented along the longest dimension of the phantoms. For the small box-shaped phantom and the elliptical phantom, a mass of 12,5 kg was used, whereas for the large box-shaped phantom a mass of 46 kg was used.

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B.5.3.3 Maximum peak spatial-average SAR measurement description

For each of the measurement configurations required in B.5.2.2.2, the maximum peak spatial-average SAR shall be evaluated in four steps.

a) Use the measurement procedures specified in 7.4 of IEC/IEEE 62209-1528:2020 or 7.3 of IEC 62209-3:2019 to determine an initial measured peak spatial-average SAR, $SAR_m(d)$, using the relevant phantom, see B.5.2.2.

b) Determine the correction factor, $CF_1(d)$, to be applied to take into account a possible increase in maximum peak spatial-average SAR due to a tissue layering effect using Equation (B.22), see IEC/IEEE 62209-1528 and [80]:

$$CF_1(d) = \begin{cases} 1 & \text{for} \quad d < 0{,}2\ \text{m} \\ \dfrac{d}{0{,}2} & \text{for}\ 0{,}2\ \text{m} \le d < 0{,}4\ \text{m} \\ 2 & \text{for}\ 0{,}4\ \text{m} \le d \le 1\ \text{m} \end{cases} \tag{B.22}$$

where

d is the EUT distance (m) measured from the liquid surface.

NOTE 1 For EUT distances above 0,2 m, the maximum peak SAR in an actual human body can exceed the maximum SAR obtained from measurements in the specified flat phantom. At a distance greater than or equal to 0,4 m, the real SAR can be up to a factor of 2 higher than the phantom SAR. The correction factor $CF_1(d)$ has been introduced to account for this effect.

c) If multiple antenna elements fed through the same port are partly loaded by the phantom, determine the correction factor, $CF_2(d)$, to account for a possible increase in maximum peak spatial-average SAR for small phantom-antenna separations related to effects of varying antenna element load conditions [81] using Equation (B.23).

$$CF_2(d) = \begin{cases} 2 & \text{for}\ d \le \dfrac{\lambda}{4} \quad \text{and}\ N_e > 1 \\ -\dfrac{4 \times d}{7 \times \lambda} + \dfrac{15}{7} & \text{for}\ \dfrac{\lambda}{4} < d < 2 \times \lambda \quad \text{and}\ N_e > 1 \\ 1 & \text{for}\ d \ge 2 \times \lambda \quad \text{or}\ N_e = 1 \end{cases} \tag{B.23}$$

where

N_e is the number of elements in the antenna array.

NOTE 2 For example, $CF_2(d)$ has a value of 1 for single element antennas.

In the interpolation function in Equation (B.23), d and λ shall both be measured in the same units (e.g. mm or m).

d) Determine maximum peak spatial-average SAR using Equation (B.24).

$$SAR_{psa}(d) = SAR_m(d) \cdot CF_1(d) \cdot CF_2(d) \tag{B.24}$$

where

d is the EUT distance (m) measured from the liquid surface;

$SAR_m(d)$ is the uncorrected measured peak spatial-average SAR averaged over either 1 g (SAR_{1g}) or 10 g (SAR_{10g});

$SAR_{psa}(d)$ is the evaluated maximum peak spatial-average SAR over either 1 g (SAR_{1g}) or 10 g (SAR_{10g}) in accordance with the averaging used in step a) for the measurement configuration.

B.5.3.4 Whole-body SAR measurement description

For each of the measurement configurations required in B.5.2.2.2, the whole-body SAR measurement is performed in two steps.

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a) Step 1: For a given separation distance from the antenna, determine the absorbed power, P_A, by measuring the electric field strength in the relevant measurement volume described by the considered exposure configuration and used phantom, see Table B.12 and Figure B.18. The measurement procedures in 7.4 of IEC/IEEE 62209-1528:2020 shall be applied whenever applicable using the following grid spacing.

   1) The maximum horizontal grid spacing shall be 20 mm for frequencies below 3 GHz and $(60/f_{GHz})$ mm for frequencies of 3 GHz and greater.

   2) The grid step in the vertical direction for a uniform spacing shall be 5 mm or less for frequencies below 3 GHz and $(10/(f_{GHz} - 1))$ mm or less but not more than 5 mm (IEC/IEEE 62209-1528:2020) for frequencies of 3 GHz and greater.

   3) If a variable spacing is used in the vertical direction, the maximum spacing between the two closest measured points to the phantom shell shall be $(12/f_{GHz})$ mm or less but not more than 4 mm. The spacing between farther points shall increase by a factor not exceeding 1,5 (IEC/IEEE 62209-1528:2020). When variable spacing is used, extrapolation routines shall be tested with the same spacing as used in measurements.

   4) To reduce the time needed to perform whole-body SAR measurements, procedures based on measurements in one or more planes can be used in combination with various techniques for numerical field propagation (e.g. [82]), provided that

      i) the procedure has been thoroughly verified, and

      ii) the uncertainty has been quantified.

b) Step 2: Evaluate the whole-body SAR, SAR_{wb}, using Equation (B.25).

$$SAR_{wb}(d) = \frac{P_A(d) \cdot CF_3(d) \cdot CF_4(f)}{M} \tag{B.25}$$

where

$P_A(d)$ is the absorbed power (watts) in the phantom measured at a distance d, the EUT distance (mm) measured from the liquid surface;

M is the mass of the body measured in kilograms. For the assessment of workers exposure or general public exposure when the lowest part of the EUT antenna is installed at 2,2 m or more above level realistically accessible by the general public, a mass of 46 kg representing adults ([61], [77]) shall be used. For the assessment of general public exposure when the lowest part of the EUT antenna is installed less than 2,2 m above level realistically accessible by the general public, a mass of 12,5 kg representing the third percentile body weight data for a four-year old girl [39] shall be used. This mass is slightly smaller than the WHO data [38] for a fifth percentile four-year-old child and leads to a conservative whole-body SAR for the general public;

$CF_3(d)$ is a correction factor to account for a possible increase in whole-body SAR due to a tissue layering effect [61], [77] specified by Equation (B.26).

$$CF_3(d) = \begin{cases} 1 + \dfrac{0{,}8 \times d}{400} & \text{for} \quad d < 400 \text{ mm} \\ 1{,}8 & \text{for} \quad d \geq 400 \text{ mm} \end{cases}; \tag{B.26}$$

$CF_4(f)$ is a correction factor to compensate for a possible bias in the obtained general public whole-body SAR when assessed using the large box-shaped phantom for child exposure configurations in accordance with Table B.13. For frequencies between the data points provided in Table B.13, a linear interpolation shall be

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used. For other exposure configurations and phantom type combinations, $CF_4(f) = 1$.

For general public (including children) exposure assessments using the large box-shaped phantom, the smaller measurement volume shall be centred at the bottom of the phantom, see also Table B.12.

Table B.12 – Phantom liquid volume and measurement volume used for whole-body SAR measurements [61], [77]

Exposure configuration	Phantom type	Phantom liquid volume m^3 $\Delta X \times \Delta Y \times \Delta Z$ or $\pi ab\ \Delta Z$	Measurement volume m^3 $\Delta X_m \times \Delta Y_m \times \Delta Z_m$ or $\pi ab\ \Delta Z_m$
Occupational and general public (adults only)	Large box-shaped phantom (preferred choice)	1,54 × 0,339 × ≥0,15	1,54 × 0,339 × 0,09
	Small box-shaped phantom	0,96 × 0,233 × ≥0,15	0,96 × 0,233 × 0,09
	Elliptical phantom	0,19 × ≥0,15	0,19 × 0,09
General public (including children)	Small box-shaped phantom (preferred choice)	0,96 × 0,233 × ≥0,15	0,96 × 0,233 × 0,06
	Large box-shaped phantom	1,54 × 0,339 × ≥0,15	0,96 × 0,233 × 0,06
	Elliptical phantom	0,19 × ≥0,15	0,19 × 0,06
NOTE 1 Where a = 300 mm is the semi-major axis of the elliptical measurement area.			
NOTE 2 Where b = 200 mm is the semi-minor axis of the elliptical measurement area.			
NOTE 3 See also Figure B.18.			

Table B.13 – Correction factor to compensate for a possible bias in the obtained general public whole-body SAR when assessed using the large box-shaped phantom for child exposure configurations [72]

Frequency MHz	300	450	900	1 800	2 600	3 500	6 000
$CF_4(f)$	2,4	2,3	1,5	1,3	1,2	1,2	1,2

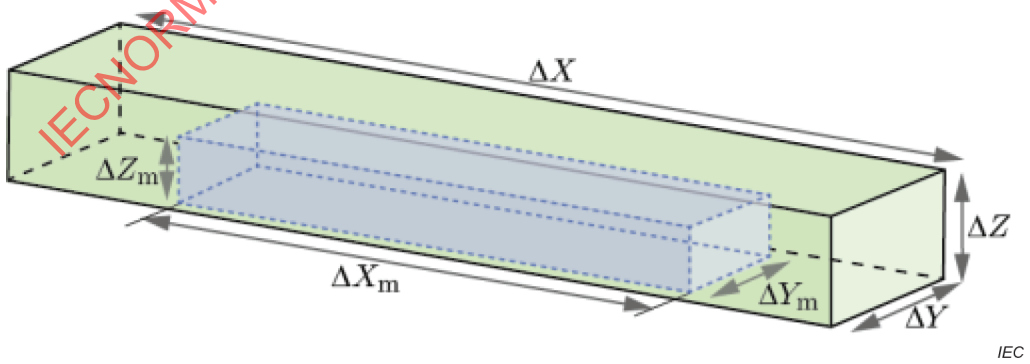


Figure B.18 – Phantom liquid volume and measurement volume used for whole-body SAR measurements with the box-shaped phantoms

B.5.4 SAR measurement uncertainty

SAR measurement uncertainty shall be estimated using the specifications in Clause 8 of IEC/IEEE 62209-1528:2020 or Clause 8 of IEC 62209-3:2019. For whole-body SAR, the templates described in Table B.14 and Table B.15 shall be used. The uncertainty associated

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with many of the influence quantities listed in IEC/IEEE 62209-1528 and the way it is assessed is applicable also for SAR measurements using the box-shaped phantoms. For some influence quantities, such as those related to the box-shaped phantoms, the description in IEC/IEEE 62209-1528 or IEC 62209-3 is not applicable. Details on how to assess the uncertainty for these influence quantities is given in Clause G.9. The SAR measurement procedure has been designed to produce results which are located on the conservative side of the probability distribution.

The expanded uncertainty with a confidence interval of 95 % shall not exceed 30 % for peak spatial-average and whole-body SAR. If the uncertainty is larger than 30 % the difference shall be added to the evaluation result before comparison with the applicable exposure limit, see Annex H.

Table B.14 – Measurement uncertainty evaluation template for EUT whole-body SAR test

Source of uncertainty	Description	Prob. distrib. type[a]	Uncertainty or semi span a (± %)	Div. δ	Sens. coeff. c	Standard uncertainty $u = a \times c/d$	ν_i
Probe calibration	IEC/IEEE 62209-1528	N		1,96	1		∞
Isotropy	IEC/IEEE 62209-1528	R		√3	1		∞
Linearity	IEC/IEEE 62209-1528	R		√3	1		∞
Probe modulation resp.	IEC/IEEE 62209-1528	R		√3	1		∞
Detection limits	IEC/IEEE 62209-1528	R		√3	1		∞
Boundary effect	IEC/IEEE 62209-1528	R		√3	1		∞
Readout electronics	IEC/IEEE 62209-1528	N		1,96	1		∞
Response time	IEC/IEEE 62209-1528	R		√3	1		∞
Integration time	IEC/IEEE 62209-1528	R		√3	1		∞
RF ambient conditions – noise	IEC/IEEE 62209-1528	R		√3	1		∞
RF ambient conditions – reflections	IEC/IEEE 62209-1528	R		√3	1		∞
Probe positioner mech. restrictions	IEC/IEEE 62209-1528	R		√3	1		∞
Probe positioning with respect to phantom shell	IEC/IEEE 62209-1528	R		√3	1		∞
Post-processing	G.9.2	R		√3	1		∞
EUT holder uncertainty	G.9.3	N		1,96	1		$M - 1$
EUT positioning	G.9.4	N		1,96	1		∞
Power scaling	IEC/IEEE 62209-1528	R		√3	1		∞
Measurement drift	IEC/IEEE 62209-1528	R		√3	1		∞
Phantom shell uncertainty	G.9.5	R		√3	1		∞
Target liquid permittivity and conductivity	G.9.6	N	2.0	1,96	1	2.0	∞
Liquid permittivity (meas.)	G.9.7	N		1,96	0,34		$M - 1$
Liquid conductivity (meas.)	G.9.7	N		1,96	0,25		$M - 1$

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Source of uncertainty	Description	Prob. distrib. type[a]	Uncertainty or semi span a (± %)	Div. δ	Sens. coeff. c	Standard uncertainty $u = a \times c/d$	ν_i
Liquid permittivity – temperature uncertainty	G.9.8	R		√3	0,34		∞
Liquid conductivity – temperature uncertainty	G.9.8	R		√3	0,25		∞
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N}\left(c_i^2 \cdot u_i^2\right)}$							
Coverage factor for required (e.g. 95 %) confidence interval, k							
Expanded uncertainty, $U = k \cdot u_c$							
NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence. NOTE 2 See Annex G for guidance on the variables in this table. [a] N – normal; R – rectangular.							

Table B.15 – Measurement uncertainty evaluation template for whole-body SAR system validation

Source of uncertainty	Description	Prob. distrib. type[a]	Uncertainty or semi span a (± %)	Div. δ	Sens. coeff. c	Standard uncertainty $u = a \times c/d$	ν_i
Probe calibration	IEC/IEEE 62209-1528	N		1,96	1		∞
Isotropy	IEC/IEEE 62209-1528	R		√3	1		∞
Linearity	IEC/IEEE 62209-1528	R		√3	1		∞
Probe modulation resp.	IEC/IEEE 62209-1528	R		√3	1		∞
Detection limits	IEC/IEEE 62209-1528	R		√3	1		∞
Boundary effect	IEC/IEEE 62209-1528	R		√3	1		∞
Readout electronics	IEC/IEEE 62209-1528	N		1,96	1		∞
Response time	IEC/IEEE 62209-1528	R		√3	1		∞
Integration time	IEC/IEEE 62209-1528	R		√3	1		∞
RF ambient conditions – noise	IEC/IEEE 62209-1528	R		√3	1		∞
RF ambient conditions – reflections	IEC/IEEE 62209-1528	R		√3	1		∞
Probe positioner mech. restrictions	IEC/IEEE 62209-1528	R		√3	1		∞
Probe positioning with respect to phantom shell	IEC/IEEE 62209-1528	R		√3	1		∞
Post-processing	G.9.2	R		√3	1		∞
Deviation of the experimental source from numerical source	IEC/IEEE 62209-1528	N		1,96	1		∞
Source to liquid distance	G.9.4	N		1,96	1		∞

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Source of uncertainty	Description	Prob. distrib. type[a]	Uncertainty or semi span a (± %)	Div. δ	Sens. coeff. c	Standard uncertainty $u = a \times c/d$	ν_i
Measurement drift	IEC/IEEE 62209-1528	R		√3	1		∞
Phantom shell uncertainty	G.9.5	R		√3	1		∞
Target liquid permittivity and conductivity	G.9.6	N	2,0	1,96	1	2,0	∞
Liquid permittivity (meas.)	G.9.7	N		1,96	0,34		$M - 1$
Liquid conductivity (meas.)	G.9.7	N		1,96	0,25		$M - 1$
Liquid permittivity – temperature uncertainty	G.9.8	R		√3	0,34		∞
Liquid conductivity – temperature uncertainty	G.9.8	R		√3	0,25		∞
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N}\left(c_i^2 \cdot u_i^2\right)}$							
Coverage factor for required (e.g. 95 %) confidence interval, k							
Expanded uncertainty, $U = k \cdot u_c$							

NOTE 1 The value of divisor δ for normal probability distribution is for 95 % confidence.

NOTE 2 See Annex G for guidance on the variables in this table.

[a] N – normal; R – rectangular.

B.6 Basic computation methods

B.6.1 General

The overview and general requirements of computational methods are specified in 8.3 and include the following.

The basic computation formulas presented in Clause B.6 are conservative formulas for the estimation of RF field strength, power density or SAR. The formulas are easy to implement and may be adequate for RF field strength and SAR evaluation. Uncertainty estimations are not required when using these formulas but there is clear guidance on where and when these formulas are applicable. The basic computation formulas can only be employed in limited applications as specified in B.6.2.

B.6.2 Basic computation formulas for RF field strength or power density evaluation

B.6.2.1 Overview of spherical and cylindrical formulas

For the sector or omnidirectional linear array configurations with arbitrary polarizations widely employed in wireless communications infrastructure, the fields in the near-field of the BS antenna have a cylindrical character [83], [84] which gradually converts to spherical in the far-field. Spherical or cylindrical formulas can be used to predict the fields radiated by these linear arrays. These estimation formulas are applicable under the conditions specified in B.6.2.2, B.6.2.4 and B.6.2.6.

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The following procedure shall be followed when performing an evaluation using the spherical or cylindrical formulas.

a) Verify that the evaluation is valid considering the restrictions and limitations of the different methods.
b) Implement Equation (B.27) through Equation (B.36).
c) Validate the implementation by comparing example results to known or published results.
d) Establish input parameters, see B.6.2.2.
e) Perform the field evaluation(s) using the formulas.
f) Report on the evaluation using the guidelines presented in Clause 10.

Simple spherical formulas are provided in B.3.1. Spherical formulas are provided in B.6.2.4 and cylindrical formulas are provided in B.6.2.5.

The coordinate system is described in accordance with Figure B.19.

The reference frame relative to an array antenna axis employed in the analytical prediction formulas for the spatially-averaged power density, $\overline{S}$, and the spatial-peak power density, S, are illustrated in Figure B.19.

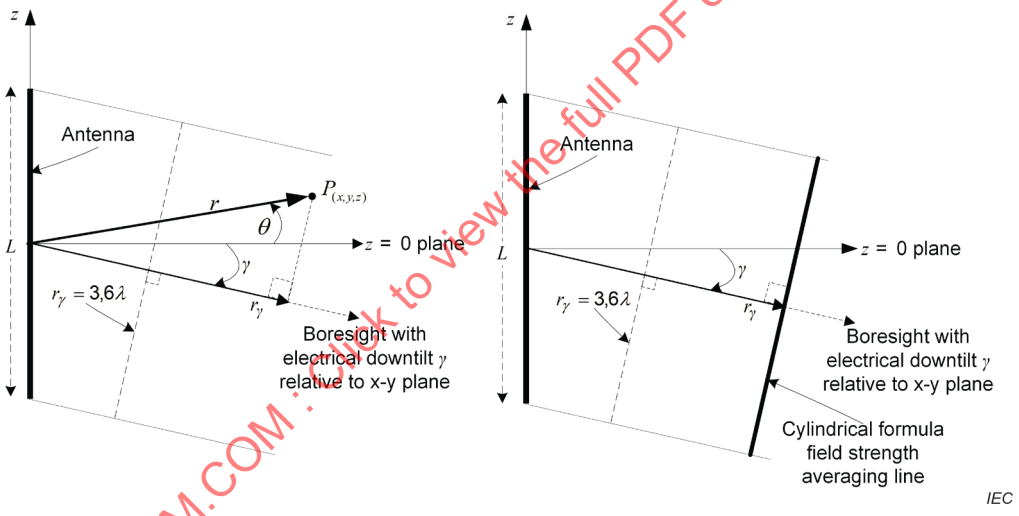


Figure B.19 – Reference frame employed for cylindrical formulas for RF field strength computation at a point P (left), and on a line perpendicular to boresight (right)

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B.6.2.2 General guidelines

Spherical formulas with different constants and cylindrical formulas can be employed for RF field strength or power density evaluations in three zones of computation around a typical linear antenna, see Figure B.20 and Table B.16. Reference [67] details how these formulas were derived and how the computed values relate to the confidence level in the different zones of computation, see Figure G.2.

NOTE The uncertainty of the computation is dependent on the exact location in relation to the antenna. For improved accuracy, in [67] four zones of computation are described with statistical analysis of extensive computational data providing uncertainty information as tables of offsets. These can be employed to determine the values of S at specific locations corrected for the required confidence level.

The spherical and cylindrical formulas use the variables specified in B.2.2 and as follows, see Figure B.1 and Figure B.19:

D is the peak antenna directivity, measured as a linear ratio, at the frequency under evaluation. If the directivity is not known, the antenna gain can be used as a substitute;

$G_{\varphi,\theta}$ is the antenna gain in direction specified in spherical coordinates at the frequency under evaluation;

G_{p} is the peak antenna gain, measured as a linear ratio, at the frequency under evaluation;

$G_{\mathrm{side_lobe}}$ is the gain, measured as a linear ratio, of the maximum side lobe in the vertical gain pattern at the frequency under evaluation;

L is the physical antenna array length measured in metres. The individual antenna lengths for each band shall be used for antennas covering more than one band;

r is the radius measured in metres taken from the centre of the antenna;

r_{γ} is the radius measured in metres along boresight of the antenna, see Figure B.19;

γ is the electrical downtilt angle measured in radians of the antenna main beam from the x-y plane (i.e. z = 0) at the frequency of evaluation and where down is positive and up is negative;

λ is the wavelength measured in metres for each band;

φ is the azimuth angle measured in radians between the positive x-axis (i.e. antenna boresight), see Figure B.1;

$\Delta\varphi_{\mathrm{3dB}}$ is the azimuth HPBW measured in radians at the frequency under evaluation.

θ is the angle measured in radians between the positive x-axis and the line formed between the origin and the evaluation location;

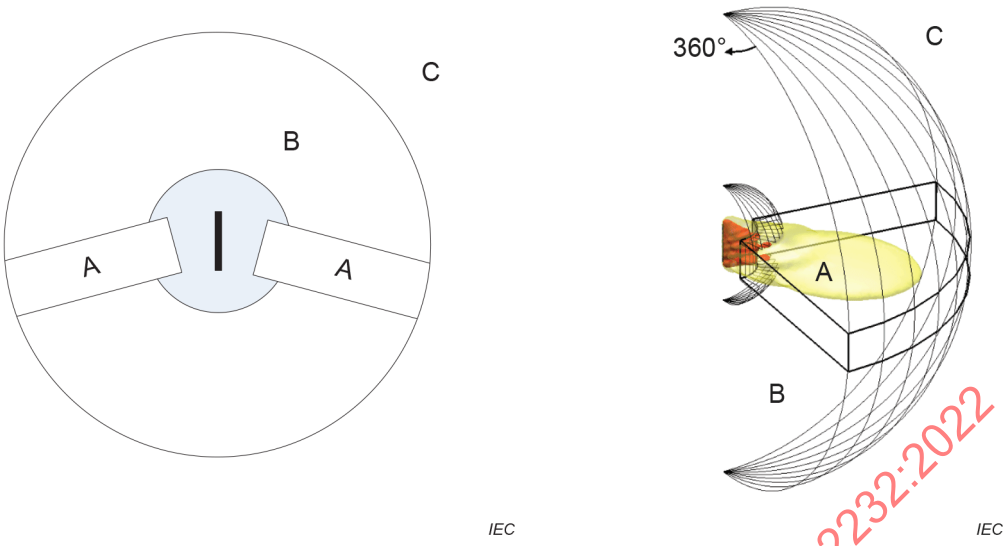
$\Delta\theta_{\mathrm{3dB}}$ is the vertical HPBW measured in radians at the frequency under evaluation.

B.6.2.3 Zone boundaries

Table B.16 gives the formulas for calculating the zone boundaries applicable to the adjusted spherical and cylindrical formulas, see Figure B.20 for visual representation of zones. These are consistent with the uncertainty analysis described in [67]. In Figure B.20, the three-dimensional view shows pie-slice sections of the same three zones, which are symmetrically equivalent around the z-axis. For antennas employing a mechanical downtilt, the zone boundaries would be rotated accordingly. The angular variables in B.6.2.4 and B.6.2.6 are defined in the coordinate system of the antenna, see Figure B.1 and Figure B.19.

NOTE The spherical formula is applicable in region II and III although when applied in region II it might lead to an overestimate of the power density.

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a) Two-dimensional view b) Three-dimensional view

Figure B.20 – Views illustrating the three valid zones for field strength computation around an antenna

Table B.16 – Definition of boundaries for selecting the zone of computation

Evaluation location in zone:	Method of calculation	Boundary restrictions		
A	Peak/Average Cylindrical formulas	$3{,}6 \times \lambda \le r_\gamma \le \max\left[\frac{2 \times L^2}{\lambda}\right.$ $\left.L/2 + 2{,}5 \times \lambda\right]$	Applicable in boresight within height of antenna[a].	Sector arrays: $-\pi / 2 \le \varphi \le \pi / 2$ Omnidirectional arrays: $-\pi \le \varphi \le \pi$
B	Peak/Average Adjusted spherical formulas	$L/2 + 2{,}5 \times \lambda \le r \le \frac{2 \times L^2}{\lambda}$	Applicable off-boresight above and below height of the antenna[a].	
C	Peak/Average Classical spherical formulas	$r \ge \max\left[\frac{2 \times L^2}{\lambda}\right.$ $\left.L/2 + 2{,}5 \times \lambda\right]$		

[a] In the case of electrical downtilt, the condition "in boresight within height of antenna" is defined by: $-\frac{L}{2} - r_\gamma \cdot \sin(\gamma) \le z \le \frac{L}{2} - r_\gamma \cdot \sin(\gamma)$ in accordance with Figure B.1 and Figure B.19.

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B.6.2.4 Adjusted spherical formulas

The adjusted spherical formulas can be employed inside parts of source regions II (spatial-peak and spatial-average RF field strength) but evaluations are limited to the zones detailed in Figure B.20. The advantage in using the adjusted spherical formulas is to obtain conservative but realistic RF field strength evaluations much closer to the antenna than with the classical far-field formulas referenced above.

Another set of relatively adjusted spherical formulas that can be used in source region II (radiating near-field) is presented in [85] and [86], which detail the limitations of the technique.

The adjusted spherical formulas for estimating both the spatially-averaged plane wave equivalent power density $\overline{S}$ and spatial-peak S plane wave equivalent power density applicable in zone B, see Figure B.20, are as follows.

a) Equation (B.27) is the adjusted spherical formula for omnidirectional arrays

$$S(r,\theta) \geq \overline{S}(r,\theta) = \frac{1{,}2 \times P \cdot G_\theta}{4\pi \cdot r^2} \quad \text{with} \quad G_\theta = 1{,}26 \times G_{\underset{\text{lobe}}{\text{side}}} + G_\text{p} \cdot 2^{-\left(\frac{\theta-\gamma}{\Delta\theta_{3\text{dB}}}\right)^2} \tag{B.27}$$

b) Equation (B.28) is the adjusted spherical formula for sector-coverage arrays

$$S(r,\varphi,\theta) \geq \overline{S}(r,\varphi,\theta) = \frac{1{,}2 \times P \cdot G_{\varphi,\theta}}{4\pi \cdot r^2} \quad \text{with} \quad G_{\varphi,\theta} = 1{,}26 \times G_{\underset{\text{lobe}}{\text{side}}} + G_\text{p} \cdot 2^{-\left(\frac{\theta-\gamma}{\Delta\theta_{3\text{dB}}}\right)^2 - \left(\frac{1{,}9\times\varphi}{\Delta\varphi_{3\text{dB}}}\right)^2} \tag{B.28}$$

NOTE 1 The adjusted spherical formulas as derived in [67] provide values of S representing the best estimate confidence level for the "technique uncertainty" considering the complete computation zone B, see Figure B.20. From [67] the corresponding upper 95 % confidence level is up to +5,8 dB on the S determined by Equation(B.27) or Equation (B.28) depending on r, φ and θ for the range of antennas evaluated in the reported study.

NOTE 2 $G_{\varphi,\theta}$ and G_θ represent models for the gain variation as function of the angular variables φ and θ.

B.6.2.5 Cylindrical formulas

B.6.2.5.1 General

The cylindrical formula can be used to evaluate the spatial-peak and spatially-averaged power density S, in the enclosed cylinder of a collinear antenna array, see Figure B.21. The cylindrical coordinate system specified in Clause B.2 is appropriate for such evaluation, see Figure B.1.

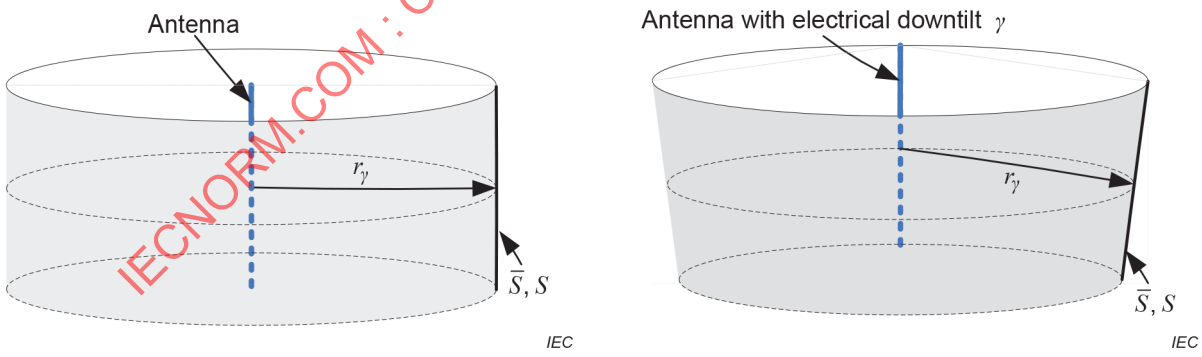


Figure B.21 – Enclosed cylinder around collinear array antennas, with and without electrical downtilt

Limitations for applying the cylindrical formulas:

a) The electrical tilt angle, γ, of the linear array shall be less than or equal to 10°. The cylindrical formulas do not take into account the formation of grating lobes near end-fire, whose power content typically becomes significant for electrical tilt angles greater than 10°.

b) The presence of reflecting surfaces/objects, reflecting ground planes and mounting structures (mast, tower, wall, etc.) in the general direction of the evaluation point is not allowed.

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B.6.2.5.2 Cylindrical estimation formulas

B.6.2.5.2.1 Spatial-average cylindrical formulas

The formulas for estimating the spatially-averaged plane wave equivalent power density $\overline{S}$ applicable in zone A, see Figure B.20, are described in [84].

a) Omnidirectional arrays – general; Equation (B.29) applies

$$\overline{S}\left(r_\gamma\right) = \frac{P}{2\pi \cdot r_\gamma \cdot L \cdot \cos^2(\gamma) \cdot \sqrt{1+\left(r_\gamma / r_0\right)^2}} \quad \text{with} \quad r_0 = \frac{1}{2} \times D \cdot L \cdot \cos^2 \gamma \tag{B.29}$$

b) Omnidirectional arrays – basic; Equation (B.30) applies

$$\overline{S}(r) = \frac{P}{2\pi \cdot r \cdot L} \tag{B.30}$$

c) Sector-coverage arrays – general; Equation (B.31) applies

$$\overline{S}\left(r_\gamma, \varphi\right) = \frac{3 \times P \cdot 2^{-\left(2 \times \varphi / \Delta\varphi_{3\text{dB}}\right)^2}}{\pi \cdot \Delta\varphi_{3\text{dB}} \cdot r_\gamma \cdot L \cdot \cos^2(\gamma) \cdot \sqrt{1+\left(r_\gamma / r_0\right)^2}} \quad \text{with} \quad r_0 = \frac{\Delta\varphi_{3\text{dB}}}{12} \cdot D \cdot L \cdot \cos^2 \gamma \tag{B.31}$$

d) Sector-coverage arrays – basic; Equation (B.32) applies

$$\overline{S}(r) = \frac{P}{\Delta\varphi_{3\text{dB}} \cdot r \cdot L} \tag{B.32}$$

NOTE 1 Equation (B.29) and Equation (B.31) compute the plane wave equivalent power density spatially-averaged over the specified antenna length L and therefore this does not necessarily relate to the spatial averaging schemes in 6.4.1 and B.3.3.

NOTE 2 The average cylindrical formulas provide values of S representing the best estimate confidence level for the "technique uncertainty". From [67], the corresponding upper 95 % confidence level is between +0,3 dB and +7,5 dB (depending on φ) above the S determined by Equation (B.29) and Equation (B.31) for the range of antennas evaluated in the reported study.

B.6.2.5.2.2 Spatial-peak cylindrical formulas

The formulas for estimating the spatial-peak plane wave equivalent power density S defined in [84] and applicable in zone A, see Figure B.20, are as follows.

a) Omnidirectional arrays – general; Equation (B.33) applies

$$S\left(r_\gamma\right) = \frac{P}{\pi \cdot r_\gamma \cdot L \cdot \cos^2(\gamma) \cdot \sqrt{1+\left(2r_\gamma / r_0\right)^2}} \quad \text{with} \quad r_0 = \frac{1}{2} \times D \cdot L \cdot \cos^2 \gamma \tag{B.33}$$

b) Omnidirectional arrays – basic; Equation (B.34) applies

$$S(r) = \frac{P}{\pi \cdot r \cdot L} \tag{B.34}$$

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c) Sector-coverage arrays – general; Equation (B.35) applies

$$S\left(r_\gamma,\varphi\right)=\frac{6\times P\cdot 2^{-\left(2\times\varphi/\Delta\varphi_{3\mathrm{dB}}\right)^2}}{\pi\Delta\varphi_{3\mathrm{dB}}\cdot r_\gamma\cdot L\cdot\cos^2\left(\gamma\right)\cdot\sqrt{1+\left(2\times r_\gamma/r_0\right)^2}}\quad\text{with}\quad r_0=\frac{\Delta\varphi_{3\mathrm{dB}}}{12}\cdot D\cdot L\cdot\cos^2\gamma \tag{B.35}$$

d) Sector-coverage arrays – basic; Equation (B.36) applies

$$S\left(r\right)=\frac{2\times P}{\Delta\varphi_{3\mathrm{dB}}\cdot r\cdot L} \tag{B.36}$$

NOTE The peak cylindrical formulas provide values of S representing the best estimate confidence level for the "technique uncertainty". From [67], the corresponding upper 95 % confidence level is between +0,6 dB and +7,2 dB (depending on φ) above the S determined by Equation (B.33) and Equation (B.35) for the range of antennas evaluated in the reported study.

B.6.2.6 Validation of spherical and cylindrical formulas

B.6.2.6.1 General

The input parameters for the validation are listed in Table B.17. The correct implementation of the formulas shall be verified by checking that the results produced by the implementation correlate within 1 % with the reference results in Figure B.23 and Figure B.22.

Angles should be converted from degrees to radians for the implementation of equations.

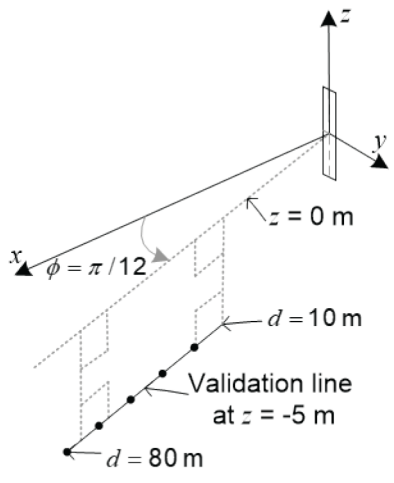
Table B.17 – Input parameters for cylindrical and spherical formulas validation

Antenna type	Freq.	RF power	Array length	Vertical HPBW	Horizontal HPBW	Electrical downtilt	Gain or directivity	Maximum side lobe gain
Omni	925 MHz	80 W	2,158 m	8°	N/A	5°	11 dBi	−9 dBi
Sector	925 MHz	80 W	2,158 m	8°	84°	5°	17 dBi	−3,6 dBi

B.6.2.6.2 Validation of spherical formulas

Using each of the implemented spherical formulas, at positions described in Figure B.22 determine S for the omnidirectional and sector-coverage antennas described in Table B.17 at positions every 10 m from d = 10 m to d = 80 m along the validation line, see Figure B.22, 5 m below the centre of the antenna and where φ = π/12 radians.

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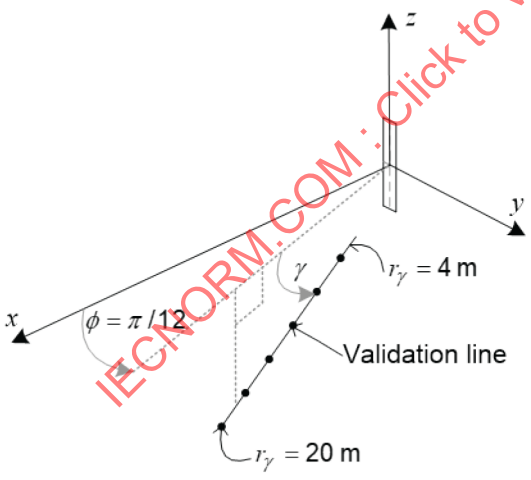
Zone	Position	Adjusted spherical		Simple spherical	
		Omni	Sector	Omni	Sector
	d (m)	S (mW m^{-2})	S (mW m^{-2})	S (mW m^{-2})	S (mW m^{-2})
B[a]	10	14,7	52,0	6,41	22,2
	20	96,3	353	7,37	26,5
C[a]	30	85,1	313	37,4	136
	40	57,1	210	41,1	150
	50	38,4	141	31,4	114
	60	26,8	98,6	22,3	81,1
	70	19,6	72,0	15,9	57,8
	80	14,8	54,5	11,6	42,1

[a] The values of S are given for reference regardless of the applicability of the formulas when considering the Table B.16 criteria.

Figure B.22 – Spherical formulas reference results

B.6.2.6.3 Validation of cylindrical formulas

For each of the implemented cylindrical formulas, determine $\overline{S}$ and S at positions every 2 m from r_γ = 4 m to r_γ = 20 m along the validation line in the main vertical beam for the omnidirectional and sector-coverage antennas described in Table B.17 and where φ = π/12 radians, see Figure B.23.



Position	Omnidirectional		Sector-coverage	
r_γ (m)	$\overline{S}$ (W m^{-2})	S (W m^{-2})	$\overline{S}$ (W m^{-2})	S (W m^{-2})
4	1,43	2,56	5,58	9,96
6	0,905	1,48	3,54	5,74
8	0,639	0,958	2,49	3,70
10	0,478	0,665	1,86	2,56
12	0,370	0,485	1,43	1,86
15	0,265	0,325	1,02	1,25
20	0,166	0,190	0,639	0,727

Figure B.23 – Cylindrical formulas reference results

B.6.3 Basic whole-body SAR and peak spatial-average SAR evaluation formulas

B.6.3.1 Applicability

For BS antennas where the radiating elements of the antenna lie on the same vertical axis, the formulas in B.6.3.2 and B.6.3.3 can be used to estimate the peak spatial-average SAR and whole-body SAR. Estimation formulas are given for three main directions: front (main beam), axial, and back in accordance with Figure B.24.

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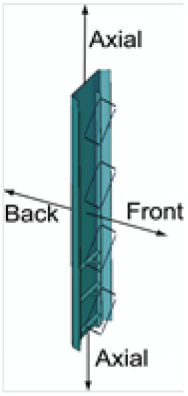


Figure B.24 – Directions for which SAR estimation expressions are provided

Table 7 summarizes recommended and permitted applications for the SAR estimation formulas ([22], [77]) in terms of the source-environment plane regions. Further constraints on the applicability of the estimation formulas are summarized in Table B.18. The original formula from the referenced paper is modified, based on geometrical considerations, to take into account the possible offset of the antenna with the exposed body and to clarify practical implementation.

Table B.18 – Applicability of SAR estimation formulas

Directions of validity	Antenna types	Frequency range MHz	Estimation value provided	Additional restrictions
Front	Directional (vertically polarized and cross-polarized) and omnidirectional BS antennas	300 to 5 000	Upper bounds of local and whole-body SAR within the main beam of the antenna	For local SAR, the phantom to antenna separation distance, d, shall be larger than Max [0,2 m; $\lambda/2\pi$] [77]. At least part of the exposed body shall be within the main beam of the antenna, i.e. $L_{eff} > 0$ (see Figure B.25) and within $\pm\varphi/2$ of main beam.
Back	Directional (vertically polarized and cross-polarized) BS antennas	600 to 2 700	Upper bound of local SAR in a plane behind the antenna oriented perpendicular to the back direction	N/A
Axial	Directional (vertically polarized and cross-polarized) and omnidirectional BS antennas	600 to 2 700	Upper bound of local SAR in a plane above (or below) the antenna oriented perpendicular to the axial direction	N/A
NOTE The frequency range is limited based on completed validation [22], [77]. Extension of the applicable frequency range and directions of validity needs further study.				

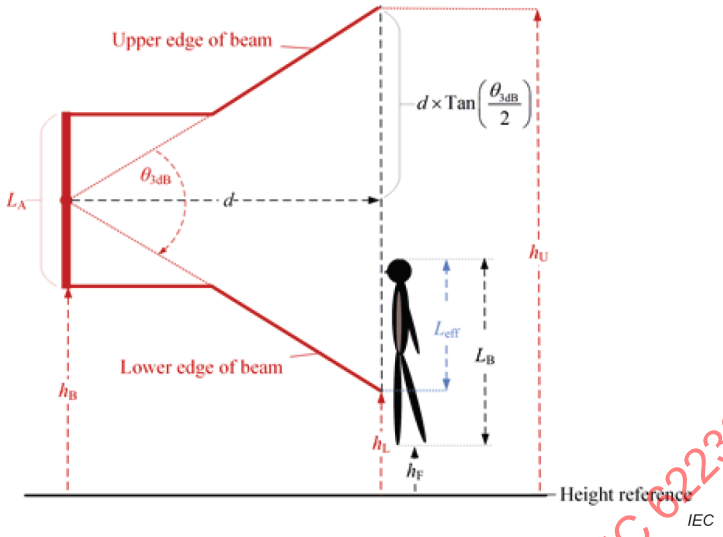
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The method can be employed for multiple sources (multiple antennas operating at the same or different frequencies), see 8.5.

B.6.3.2 SAR estimation formulas applicable to the front (main beam) direction

The variables used for the calculation of local and whole-body SAR are described in Figure B.25.

It is assumed that the exposed body is located in front of the antenna in the main beam direction with arbitrary vertical displacement from the main beam centre.



where

h_B is the height (above reference), expressed in metres, of the base of the antenna;

h_U is the height (above reference), expressed in metres, of the upper edge of the antenna beam at horizontal distance d in front of the antenna element;

h_L is the height (above reference), expressed in metres, of the lower edge of the antenna beam at horizontal distance d in front of the antenna element (minimum value 0 when beam meets height reference);

h_F is the height of the feet above reference expressed in metres;

L_A is the physical antenna array length expressed in metres;

L_B is the length of the body;

L_{eff} is the effective length of the body expressed in metres (i.e. the overlap between antenna beam and body).

Figure B.25 – Description of SAR estimation formulas physical parameters

The whole-body SAR and peak spatial-averaged SAR (1 g or 10 g) shall be evaluated using Equation (B.37), Equation (B.38) and Equation (B.39), derived from [38], [39], [77] considering a whole-body mass of 46 kg for adults and 12,5 kg for children, see 8.2.3:

$$\mathrm{SAR_{wb}} = A(f,d) \cdot \frac{L_{\mathrm{eff}}}{\mathrm{CF_B} \cdot L_B} \cdot \frac{P}{\Delta\varphi_{3\mathrm{dB}} \cdot L_A \cdot d} \cdot \left[1 + \left(\frac{4\pi \cdot d}{\Delta\varphi_{3\mathrm{dB}} \cdot D_A \cdot L_A}\right)^2\right]^{-1/2} \quad \text{(B.37)}$$

$$\mathrm{SAR_{10g}} = 25 \times \mathrm{SAR_{wb}} \cdot \frac{L_B}{L_{\mathrm{eff}}} \cdot \frac{1}{\mathrm{CF_{wb/10g}}} \quad \text{(B.38)}$$

$$\mathrm{SAR_{1g}} = 20 \times \mathrm{SAR_{wb}} \cdot \frac{L_B}{L_{\mathrm{eff}}} \cdot \frac{1}{\mathrm{CF_{wb/1g}}} \quad \text{(B.39)}$$

where

$\mathrm{SAR_{wb}}$ is the whole-body SAR, evaluated for adults or children;

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SAR_{10g} is the peak spatial-averaged SAR 10 g evaluated for adults or children;

SAR_{1g} is the peak spatial-averaged SAR 1 g evaluated for adults or children;

$A(f,d)$ is a coefficient specified in Table B.19;

CF_B is a coefficient that equals 0,089 m for adults and 0,06 m for children;

L_B is the length of the body;

d is the closest distance expressed in metres from the antenna element to the evaluation point. If the distance to the antenna elements is not known, d can be taken conservatively as the distance to the antenna radome;

D_A is the directivity of the array in the main beam (linear ratio);

L_{eff} is the effective length of the body expressed in metres (i.e. the overlap between antenna beam and body, see Figure B.25);

L_A is the physical antenna array length expressed in metres;

$\Delta\varphi_{3dB}$ is the horizontal half-power beamwidth of the antenna expressed in radians;

$\Delta\theta_{3dB}$ is the vertical half-power beamwidth of the antenna;

$CF_{wb/10g}$ is a coefficient applicable to SAR_{10g};

$CF_{wb/1g}$ is a coefficient applicable to SAR_{1g}.

$CF_{wb/10g}$ and $CF_{wb/1g}$ shall take the values in Equation (B.40) and Equation (B.41), respectively.

$$CF_{wb/10g} = \begin{cases} 1{,}5 & \text{for} \quad 300\ \text{MHz} < f \le 2{,}5\ \text{GHz} \\ 1 & \text{for} \quad 2{,}5\ \text{GHz} < f < 5\ \text{GHz} \end{cases} \tag{B.40}$$

$$CF_{wb/1g} = \begin{cases} 0{,}6 & \text{for} \quad 300\ \text{MHz} < f \le 2{,}5\ \text{GHz} \\ 0{,}3 & \text{for} \quad 2{,}5\ \text{GHz} < f < 5\ \text{GHz} \end{cases} \tag{B.41}$$

L_B shall be set to 1,54 m for adults and 0,96 m for children for consistency with B.5.2.2.1. The individual antenna lengths L_A for each band shall be used for antennas covering more than one band. L_{eff} shall be evaluated using Equation (B.42), Equation (B.43) and Equation (B.44).

$$L_{eff} = \max\left[\min\left(h_U ; h_F + L_B\right) - \max\left(h_L ; h_F\right); 0\right] \tag{B.42}$$

where

$$h_U = \max\left[h_B + L_A ; h_B + \frac{L_A}{2} + d \cdot \tan\left(\frac{\Delta\theta_{3dB}}{2}\right)\right] \tag{B.43}$$

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and

$$h_L = \max\left\{\min\left[h_B\,;\,h_B + \frac{L}{2} - d\cdot\tan\left(\frac{\Delta\theta_{3dB}}{2}\right)\right];0\right\} \tag{B.44}$$

The coefficient $A(f,d)$ shall be evaluated using Table B.19. The distance dependence behaviour is included to describe the effect of tissue layering discussed in B.5.3.3.

Table B.19 – Calculation of $A(f, d)$

f (MHz)	$A(f,d)$ ($m^3\ kg^{-1}$)	
300 to 900	$\left(3{,}5 + \frac{f-300}{600}\right)(1+2\times d)\cdot 10^{-4}$	for 0,2 m ≤ d ≤ 0,4 m
	$\left(6{,}3 + 1{,}8\times\frac{f-300}{600}\right)\cdot 10^{-4}$	for d > 0,4 m
900 to 5 000	$4{,}5\times(1+2\times d)\cdot 10^{-4}$	for d ≤ 0,4 m
	$8{,}1\cdot 10^{-4}$	for d > 0,4 m

B.6.3.3 SAR estimation formulas applicable to the axial and back directions

Peak spatial-average SAR (1 g or 10 g) values shall be evaluated using Equation (B.45) and Equation (B.46), see [22]:

$$SAR_{axial} = CF\cdot\frac{P}{N_e\cdot\max(d\,;0{,}01)} \tag{B.45}$$

$$SAR_{back} = \frac{CF}{10}\cdot\frac{P}{N_e\cdot\max(d\,;0{,}01)} \tag{B.46}$$

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where

CF is a coefficient that equals 0,1 for SAR_{1g} and 0,05 for SAR_{10g};

d is:

- in the back direction, the distance measured in metres from the antenna back plate to the evaluation point;
- in the axial direction, the smallest distance measured in metres from the nearest antenna element to the evaluation point. For a conservative evaluation, the distance from the antenna radome can be used in the axial direction;

NOTE For comparison with full wave-simulations, d is the closest distance between the phantom and either the back plate for the back direction evaluation or the nearest antenna element for the axial direction evaluation.

N_e is the number of antenna elements at the frequency of evaluation.

B.6.3.4 Using the SAR estimation formulas

The following procedure shall be followed when employing the SAR estimation formulas.

a) Verify that the evaluation is valid considering the restrictions and limitations of the method.
b) Implement the formulas presented in B.6.3;
c) Validate the implementation against the results presented in B.6.3.7;
d) Establish input parameters, see B.6.3.5;
e) Perform the SAR evaluation(s) using the validated implementation.
f) Prepare the evaluation report using Clause 10 guidelines.

B.6.3.5 Input parameters for SAR estimation formulas

To apply the SAR estimation formulas for child and adult, the following information is required:

a) frequency bands for all transmitters;
b) P, N_e, $\Delta\varphi_{3dB}$, $\Delta\theta_{3dB}$, D, see B.2.2;
c) L_A, the physical antenna array length for each band expressed in metres;
d) h_B, the height above local walking or standing surface reference of the base of the physical antenna expressed in metres;
e) h_F, the standing height above local walking or standing surface reference of the exposed person expressed in metres.

If the number of antenna elements is not known, Equation (B.47) shall be used, see [65]:

$$N_e = L_A / (0{,}85 \times \lambda) \tag{B.47}$$

rounded to the nearest integer.

B.6.3.6 SAR estimation formulas uncertainty

The SAR estimation formulas provide a conservative estimate (using a 95 % confidence level) of local and whole-body SAR provided that the input parameters are chosen within their range so as to maximize the estimated value.

B.6.3.7 Verification of SAR estimation formulas

The correctness of an implementation of these formulas shall be verified for the front, back and axial directions as described in Figure B.24 using the antenna parameters in Table B.20 and cases specified in Table B.21 and Table B.22. Cases in Table B.21 and Table B.22 include validation of applicability constraints, with a "–" SAR value indicating that the test case is outside the applicability range.

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Table B.20 – Antenna parameters for SAR estimation formulas verification

Antenna no.	Array length (m)	Directivity[a] (dBi)	Horiz. HPBW[a] (°)	Vert. HPBW[a] (°)	Number of elements
1	2	14,7	65	10,5	6
2	2	15	64	8,9	7
3	1.2	16,7	60	5,6	12
4	0,85	15,1	91	7,1	12

[a] The SAR estimation formulas require directivity to be expressed as a linear value, and horizontal half power beamwidth to be expressed in radians.

Table B.21 – Verification data for SAR estimation formulas – front

Antenna no. (Table B.19)	Frequency (MHz)	Power (W)	Antenna base height (m)	Child or Adult	Foot height (m)	Dist *d* (m)	SAR_{wb}[a] (W kg^{-1})	SAR_{10g}[a] (W kg^{-1})	SAR_{1g}[a] (W kg^{-1})
1	699	1	1,5	A	1,5	0,3	1,10E−02	1,83E−01	3,66E−01
1	701	1	1	C	0	1	–	–	–
1	701	1	1,6	C	0.2	15	–	–	–
1	701	1	1	C	3,2	13	–	–	–
1	696	1	1	C	3	13	3,25E−05	2,67E−03	5,35E−03
1	701	1	1	C	0	1	–	–	–
2	950	1	1	A	1,1	15	9,53E−05	1,59E−03	3,18E−03
2	950	1	1	C	1,1	15	1,41E−04	2,36E−03	4,71E−03
2	885	1	1	A	1,1	0,19	–	–	–
2	905	1	1	A	1,1	0,19	1,64E−02	–	–
3	2 495	1	1	A	0	0,5	5,05E−03	2,40E−01	4,80E−01
3	2 505	1	1	A	0	0,5	5,05E−03	3,60E−01	9,60E−01

[a] The "–" designates a "formula not applicable" result validating the correct implementation of applicability checks.

Table B.22 – Verification data for SAR estimation formulas – axial and back

Antenna no. (Table B.19 and Table B.20)	Frequency (MHz)	Power (W)	Dist *d* (m)	Axial		Back	
				SAR_{10g}[a] (W kg^{-1})	SAR_{1g}[a] (W kg^{-1})	SAR_{10g}[a] (W kg^{-1})	SAR_{1g}[a] (W kg^{-1})
1	699	1	0,1	–	–	–	–
1	700	1	0,01	8,33E−01	1,67E+00	8,33E−02	1,67E−01
1	700	1	0,001	8,33E−01	1,67E+00	8,33E−02	1,67E−01
1	700	1	0,02	4,17E−01	8,33E−01	4,17E−02	8,33E−02
4	2 700	1	0,1	4,17E−02	8,33E−02	4,17E−03	8,33E−03
4	2 701	1	0,1	–	–	–	–

[a] The "–" designates a "formula not applicable" result validating the correct implementation of applicability checks.

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B.6.4 Basic compliance boundary assessment method for BS using parabolic dish antennas

B.6.4.1 General

Dish antennas (or parabolic antennas) are generally deployed for radio-relays or point-to-point communication systems (microwave links), which typically operate at frequencies from 1,4 GHz up to 200 GHz and beyond. Typical point-to-point systems are characterized by a gain value above 30 dBi, and lower emission outside the main beam.

Microwave links are installed on towers, masts, rooftops or in similar locations. The main design criterion involves an unobstructed line-of-sight path between the transmit and receive endpoints. If a line-of-sight path cannot be established, high diffraction losses can occur, resulting in a non-viable communications path.

Outdoor units and antennas are typically positioned in areas that are inaccessible by the general public; this prevents human overexposure and damage to the equipment or to the radio link. This establishes a special condition for these systems: the radio propagation path is not accessible to members of the general public.

The basics of antenna physical parameters relevant for the RF exposure evaluation of dish antennas can be found in ETSI TR 102 457 [59]. This technical report also reviews far-field analysis principles as well as near-field evaluation based on simulation methods and measurements calibration. It includes measurement and calculation results on real systems that have been used to establish the evaluation method described in B.6.4.2 and to provide an estimation of its accuracy.

As described in 5.4 of [37], below 10 GHz (or 6 GHz depending on the applicable exposure limits), the power density can be used to derive a conservative value of local SAR using Equation (B.48).

$$\frac{\mathrm{SAR}_{\mathrm{local}} \cdot m_0}{A_0} \leq S \tag{B.48}$$

where

$\mathrm{SAR}_{\mathrm{local}}$ is the local SAR value averaged over a mass m_0;

m_0 is the reference mass 10 g for spatial averaging (or 1 g depending on the applicable exposure limits);

A_0 is the reference area used for spatial averaging;

S is the power density.

In this frequency range, by assuming $S \leq S_{\mathrm{lim}}$ refers to $\mathrm{SAR} \leq \mathrm{SAR}_{\mathrm{lim}}$, compliance criteria based on S_{lim} can be considered as a conservative assessment based on local SAR. In other words, compliance with reference levels is equivalent to compliance with basic restrictions.

B.6.4.2 Compliance boundary of a dish antenna

In order to assess human exposure to RF from dish antennas, the maximum power density from these antennas is generally derived from the following parameters: transmitted power, frequency, antenna diameter, aperture efficiency and antenna gain. The compliance boundary parameters are described in Figure 9.

As described in [37], the compliance boundary of a dish antenna shall be evaluated in accordance with the flowchart presented in Figure B.26, which applies to both general public

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and occupational exposure situations. The compliance boundary parameters are based on the following assumptions.

a) Compliance touch means that exposure limits are not exceeded while touching the radome of the equipment under test (EUT).

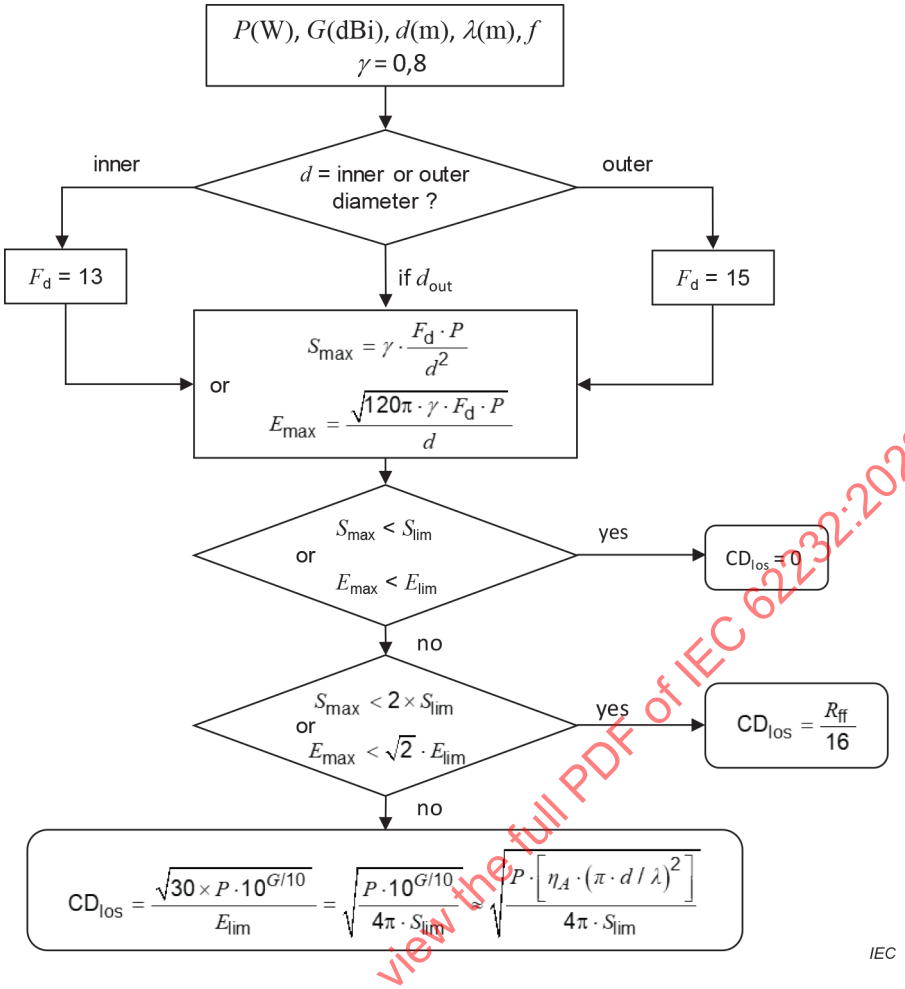
b) The coefficient γ (0,8) relates to the 1 dB attenuation due to spatial averaging in a plane perpendicular to the antenna main lobe at frequencies between 10 GHz and 300 GHz.

c) The compliance boundary, if not zero, is a cylinder defined by the line-of-sight (LoS) axis and the outer diameter d_{out} up to the compliance distance CD_{los}, see Figure 9.

NOTE Use of a cylinder as the compliance boundary does not always consider side lobes appropriately for certain types of less-directive aperture antennas (i.e. gain less than or equal to 25 dBi), including but not limited to antennas that employ grid reflectors as opposed to solid-surface reflectors. In this case, an alternative model potentially worth considering has been developed in [87].

Rectangular antennas used for radio-relays or point-to-point communication systems (microwave links) are generally patch antenna arrays rather than rectangular horn or reflector antennas as described in [88]. For such patch array antennas, the measurement or computation methods such as those described in B.3.1, B.3.2, B.4, B.6 or B.7 (e.g. synthetic model) should be used.

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where

γ is a factor used for spatial averaging;

F_d is a multiplication factor depending on the dish antenna diameter;

λ is the wavelength (m);

A_0 is the reference area used for spatial averaging;

CD_{los} is the compliance distance in the line of sight;

d is the diameter of the parabolic dish antenna (m), can be equal to d_{in} (inner diameter) or d_{out} (outer diameter), or diagonal of a rectangular horn or reflector antenna;

G is the antenna gain;

m_0 is the reference mass for spatial averaging – 10 g or 1 g depending on the applicable exposure limits;

P is the power transmitted to the antenna;

r is the distance between the evaluation location and the antenna;

R_{ff} is the far-field distance $R_{ff} = \frac{2 \times D^2}{\lambda}$ (see A.1.3);

S is the power density (W m^{-2}) at distance r (m) from the antenna;

S_{lim} is the applicable limit for power density (W m^{-2});

S_{max} is the maximum value used for the power density spatially averaged over 20 cm^2;

E_{lim} is the applicable limit for E-field strength (V m^{-1});

E_{max} is the maximum value used for the E-field strength (V m^{-1});

SAR_{lim} is the applicable limit for local SAR for m_0.

Figure B.26 – Flow chart for the simplified assessment of RF compliance boundary in the line of sight of a parabolic dish antenna

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B.6.5 Basic compliance boundary assessment method for intentionally radiating cables

Figure B.27 shows the geometry of a typical intentionally radiating cable (also known as leaky feeder), consisting of a coaxial cable whose metallic sheath or braid features regularly spaced slots that leak out a small fraction of the RF energy guided inside the cable. Therefore, the guided wave attenuation in the cable consists of two components: the conventional field attenuation due to ohmic and dielectric losses in the cable materials, and the guided field attenuation due to energy loss in the form of leaked radiation.

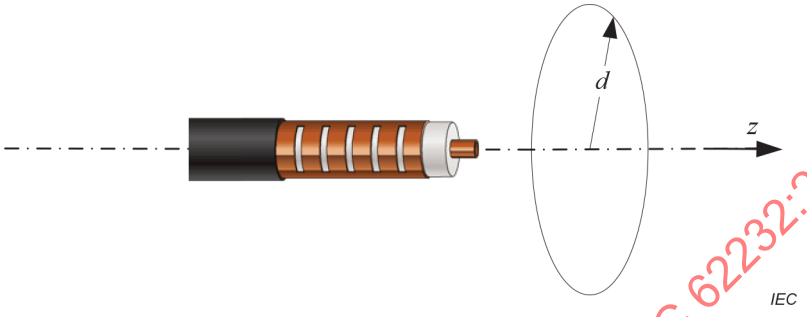


Figure B.27 – Radiating cable geometry

Because of the aforementioned characteristics, radiating cables are radiating transmission lines frequently employed to provide coverage in tunnels or indoors, characterized by a frequency dependent cable attenuation coefficient, α, see Equation (B.49):

$$\alpha = \alpha_d + \alpha_r \tag{B.49}$$

where

α_d is the cable attenuation coefficient due to dissipation loss along the transmission line (dB m^{-1});

α_r is the cable attenuation coefficient due to radiation loss along the transmission line (dB m^{-1}).

Neglecting dissipative cable attenuation and assuming that all guided field attenuation is due to RF leakage, i.e. $\alpha_d = \alpha_r$, allows overestimating the relative fraction of radiated RF power, which leads to a conservative RF field strength evaluation. Under this hypothesis, the travelling power decay versus distance along the transmission line (assuming that the cable is fed at $z = 0$) is calculated using Equation (B.50).

$$P(z) = P \cdot 10^{-z \cdot \left(\frac{\alpha}{10}\right)} = P \cdot e^{-\alpha \cdot z \cdot \left[\frac{\ln(10)}{10}\right]} = P \cdot e^{-z \cdot \left[\frac{\alpha}{4{,}343}\right]} \tag{B.50}$$

Therefore, the radiated power per unit length P_r (W m^{-1}) is calculated with Equation (B.51).

$$P_r(z) = \left.\frac{P(z) - P(z+\Delta z)}{\Delta z}\right|_{\Delta z \to 0} = -\frac{\partial}{\partial z} P(z) = P \cdot \left(\frac{\alpha}{4{,}343}\right) \cdot e^{-z \cdot \left(\frac{\alpha}{4{,}343}\right)} \tag{B.51}$$

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Since the waves emitted from radiating cables generally feature conical character, it is possible to produce a conservative estimate of the emitted power density (W m^{-2}) at a radial distance d by introducing a cylindrical-type decay using Equation (B.52).

$$S(d,z) = \frac{P_r(z)}{2\pi \cdot d} = \left(\frac{\alpha}{4{,}343}\right) \cdot \frac{P}{2\pi \cdot d} \cdot e^{-z \cdot \left(\frac{\alpha}{4{,}343}\right)} \quad \text{(B.52)}$$

The power density (W m^{-2}) estimate can be made even more conservative by taking its peak, at z = 0 using Equation (B.53).

$$S(d) = \frac{P \cdot \alpha}{8{,}646 \times \pi \cdot d} \quad \text{(B.53)}$$

where

$S(d)$ is the power density (W m^{-2}) at radial distance d (m) from the centre of the leaky feeder at the feed connector;

$S(d,z)$ is the power density (W m^{-2}) at radial distance d (m) from the centre of the leaky feeder at a distance z (m) from the feed connector;

α is the frequency-dependent cable attenuation coefficient (dB/m);

P is the time-averaged power (W) transmitted into the leaky feeder.

Equation (B.53) can be considered a conservative estimate of the exposure on a person disposed parallel to the cable axis. Since cables normally run horizontally in tunnels or offices, Equation (B.53) provides a very conservative evaluation when applied at the closest radial distance where any portion of the exposed person's body is relative to the cable longitudinal axis.

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B.7 Advanced computation methods

B.7.1 General

For some scenarios more accurate evaluation can be required, for example field evaluation in the near-field of an antenna or SAR evaluations to the side of a BS antenna. The advanced computation techniques are presented in Clause B.7, with specific guidance on how these methods shall be employed (typically, but not necessarily, using commercially available software). If an advanced method is selected, a full uncertainty analysis shall be performed. The subclauses on uncertainty related to each advanced computation method present the minimum uncertainty parameters that shall be considered.

B.7.2 Synthetic model and ray tracing algorithms

B.7.2.1 Applicability of synthetic model and ray tracing algorithms

The synthetic model is used to calculate the electric field strength at an observation point using a vector sum of a number of small "patches" of the EUT antenna treated as separate sources [89]. The synthetic model can be used alone for free space exposure evaluation or together with the ray tracing algorithms to take into account the environment (e.g. ground, walls).

This model is applicable in the radiating near-field and far-field regions.

The electric field strength at an evaluation point can be obtained by a vector sum of n small patches of the antenna, treated as separate sources as specified in Equation (B.54):

$$E(\varphi,\theta) = \sum_n \alpha_n \frac{\sqrt{30 \times P_n \cdot G_n(\varphi,\theta)}}{r_n} e^{j(\gamma_n + \frac{2\pi \cdot r_n}{\lambda})} \quad \text{(B.54)}$$

where

r_n is the distance between the observation point and reference point of patch n;

P_n is the input power into patch n;

γ_n is the relative phase of applied voltage at antenna patch n;

$G_n(\varphi,\theta)$ is the gain of patch n towards the evaluation point relative to an isotropic antenna, see [90];

α_n is the weighting coefficient.

The patch gain $G_n(\varphi,\theta)$ can be determined in accordance with references given in [89].

Various ray tracing algorithms have been developed (e.g. [65], [83], [84], [89], [91]) and implemented in commercial computer codes, for the evaluation of RF field strength or power density in all directions around BS antennas.

These ray tracing algorithms are suited to evaluations in the far-field (source region III) and radiating near-field (source region II). Table 7 summarizes recommended and permitted applications for ray tracing methods. Typical implementations involve one, two or multi-rays. Applicability of each of these is discussed below.

a) Ray tracing – one-ray

   1) Typically used for evaluation of RF field strength or power density in the far-field or radiating near-field of one or more sources with no or negligible environmental reflectors (source-environment plane regions III-0 and II-0). For example towers, masts and poles.

   2) Can also be used in more complex environments but a more comprehensive uncertainty analysis is then required.

   3) Alternatively, the method can be enhanced by employing a factor to account for average ground reflection (6.2.8), for example as done in US FCC OET Bulletin 65 [37], where the factor is 1,6 for RF field strength (2,56 for power density) (source-environment plane II-1 and III-1).

b) Ray tracing – two-ray

   1) Typically used for evaluation of RF field strength or power density in the far-field or radiating near-field (source-environment plane II-1 and III-1) of one or more sources with one environmental reflector, for example roof-top reflection or ground reflection in open and semi-built up areas.

   2) Can also be used in more complex environments but a more comprehensive uncertainty analysis is then required.

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c) Ray tracing – multi-ray

1) Typically used for evaluation of RF field strengths or power density in the far-field or radiating near-field of one or more sources with more than one environmental reflector (source-environment plane regions II-M and III-M), for example complex roof-tops, or complex built-up areas.

2) This method would theoretically provide more accurate results than the one-ray or two-ray techniques, but for this to be the case very detailed and accurate information is required on the multiple environmental objects. In practice, one-ray or two-ray methods with appropriate uncertainty analysis taking possible multiple environmental reflectors into account would be appropriate.

B.7.2.2 Input requirements for synthetic model and ray tracing algorithms

The input requirements for synthetic model are listed below:

r_n distance between the observation point and reference point of patch n;

P_n input power into patch n;

γ_n relative phase of applied voltage at antenna patch n;

$G_n(\varphi,\theta)$ gain of patch n towards the evaluation point relative to an isotropic antenna, see [90];

α_n weighting coefficient.

The input data requirements for ray tracing techniques are listed below:

a) transmitted power;

b) RF transmission system losses;

c) antenna gain;

d) antenna aperture;

e) antenna pattern;

f) antenna mounting height, position and orientation;

g) environmental clutter data (ground, buildings);

h) topography.

If one or more of the input data values are unknown, ray tracing can still be used provided the uncertainty estimation includes additional sources of uncertainty relating to the estimated data values.

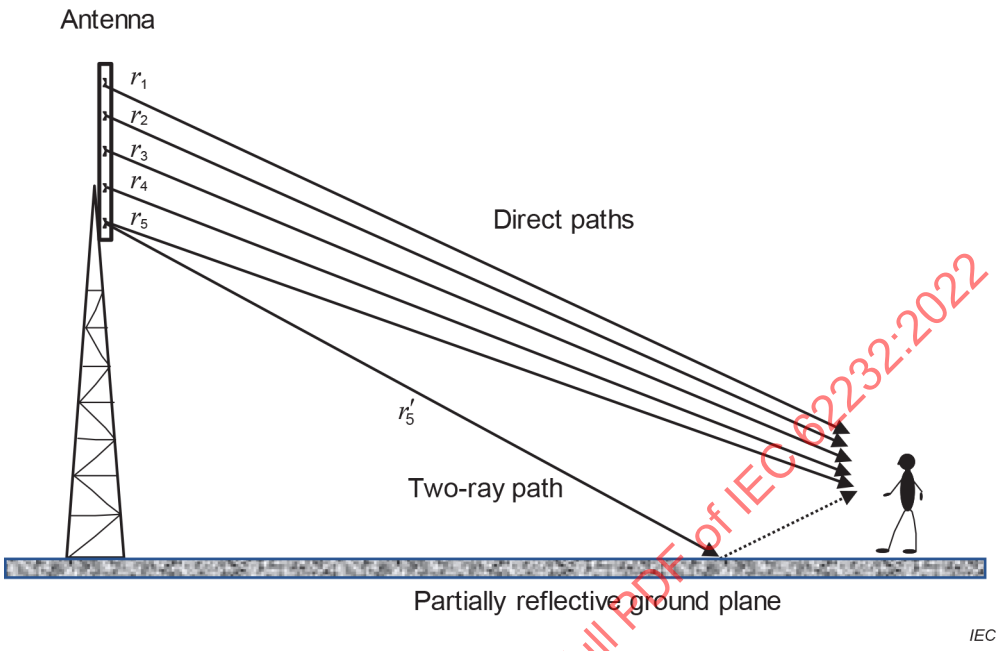
B.7.2.3 Description of synthetic model and ray tracing algorithms

Synthetic model and ray tracing algorithms employ a simple approach which uses antenna pattern synthesis and spherical free-space wave propagation to calculate approximate field values in the radiating near-field as well as the far-field of antennas (source-environment plane regions II-* and III-*). The antenna parameters (gain, horizontal and vertical far-field radiation pattern cuts) are typically obtained from manufacturers' published data. Technical details for implementing ray tracing algorithms can be found in, for example, [65], [83], [84], [89], [91].

Figure B.28 shows the typical geometry and parameters to apply ray tracing with the synthetic model where r_1 to r_5 represent the direct path from (e.g. [65], [83], [84], [89], [87]) the centre of the five individual radiating elements in the array to the evaluation point and r_5' represents the two-ray path from the lowest element of the array reflecting from the ground to the evaluation location.

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Ray tracing algorithms typically overestimate the RF field strength due to absorption of RF energy in the ground, building walls and other man-made structures that are not taken into account with basic implementations. This overestimation shall form part of the uncertainty analysis.



NOTE The two-ray paths r_1' to r_4' are not shown in the figure but can be included in the model for a more accurate computation.

Figure B.28 – Synthetic model and ray tracing algorithms geometry and parameters

The following procedure shall be followed when employing ray tracing algorithms.

a) Verify that the evaluation is valid considering the restrictions and limitations of the method.
b) Select commercial code or implement algorithms.
c) Validate using pre-calculated examples, see B.7.2.5.
d) Establish input parameters, see B.7.2.2.
e) Perform evaluation (apply ray tracing algorithm).
f) Perform uncertainty analysis, see B.7.2.4.
g) Apply uncertainty for result interpretation, see Clause 9 and Annex G.
h) Report on evaluation, see Clause 10.

B.7.2.4 Synthetic model and ray tracing uncertainty parameters

Uncertainty factors for ray tracing fall into three categories, namely transmitter system, modelling technique and environmental uncertainties. Table B.23 identifies the leading uncertainty factors for these three categories. The surveyor shall understand and test for each applicable source of uncertainty.

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Table B.23 – Example template for estimating the expanded uncertainty of a synthetic model and ray tracing RF field strength computation

Source of uncertainty	Unit	Prob. distrib. type	Uncertainty or semi span	Divisor	Sens. coeff.	Standard uncertainty	Corr. fact.	$c^2 \cdot u^2$
			a	δ	c	$u = a/\delta$	CF	
System								
Variation in the power of the RF transmitter from its nominal level	dB	rect.		√3	1			
Cable/connector losses	dB	normal		1,96	1			
Mismatch between antenna and its feed	dB	U-shape		√2	1			
Antenna radiation pattern data[a]	dB	normal		1,96	1			
Antenna positioning, mounting and support structure	dB	rect.		√3	1			
Technique uncertainties								
Inherent uncertainties associated with the approximate numerical model used to represent the antenna.	dB	rect.		√3	1			
Null-filling of antenna patterns (if applied)	dB	Depends on algorithm			1			
Environmental uncertainties								
Scattering from nearby objects and the ground	dB	rect.		√3	1			
Uncertainty in using electric field strength evaluations to estimate magnetic field strength, or vice versa	dB	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} (c_i^2 \cdot u_i^2)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								

NOTE 1 See Annex G for guidance on the variables in this table.

NOTE 2 It is assumed that the logarithmic expression of the measured quantity can be treated similarly to that of the linear expression in view of the statistical properties of the measured quantity.

NOTE 3 The value of divisor δ for normal probability distribution is for 95 % confidence.

[a] The normalized radiation pattern uncertainty can be different inside the HPBW (very small); outside the main beam (larger); and in the side lobes.

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B.7.2.5 Validation of synthetic model and ray tracing algorithms

The following provides an example for validating the correct implementation of a synthetic model and ray tracing algorithm using the generic panel BS antenna. This antenna has nine dipole radiators and operates in the 900 MHz band. It is highly recommended that several examples are checked to make sure the near-field power density error does not exceed ±3 dB.

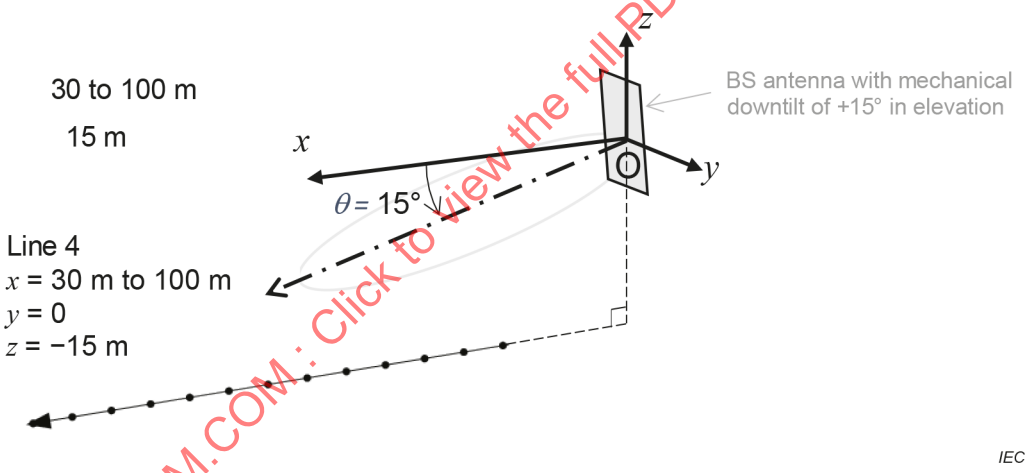
a) The antenna parameters for the synthetic model and ray tracing algorithms validation are given in Figure B.30. A point-source array model or aperture field representation shall be extracted using these patterns.

b) The power density values shall be determined for a frequency of 925 MHz and P of 80 W along line 1, line 2 and line 3, see Figure B.32, in the near-field of the antenna, and on line 4, see Figure B.29, in the far-field.

c) The determined power density values shall be compared with the reference power density values in Table B.24.

NOTE The results obtained with the synthetic model and ray tracing algorithms are compared to results obtained from a full wave simulation. The results compare very well on lines 1, 2 and 4. The ray tracing algorithm ignores polarization of the electric fields and for this reason the results very close to the antenna on line 3, differ slightly more when compared to the full wave solution. This is however expected and within the uncertainty range of a typical ray tracing algorithm.

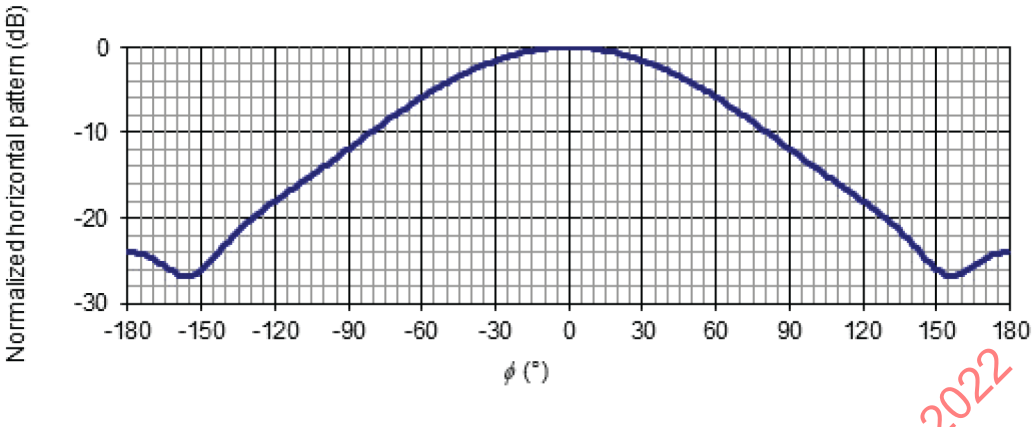
If the maximum deviation from the reference results is within ±3 dB, the simulation package has passed the example validation.



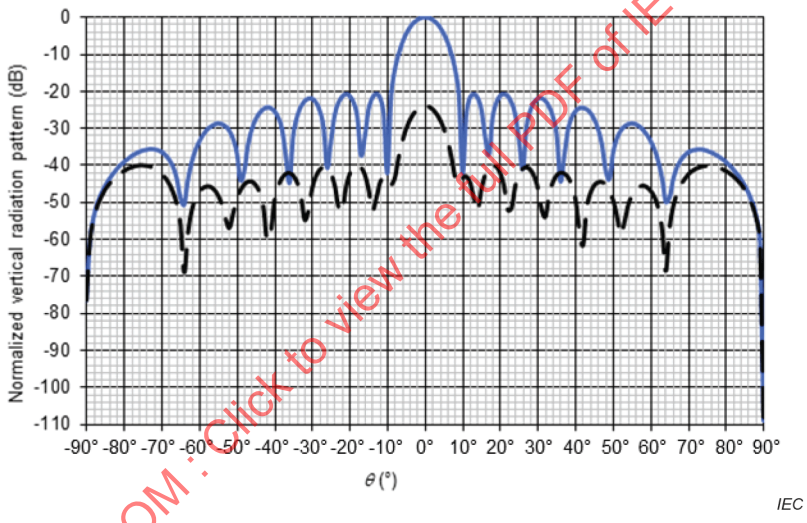
NOTE Line 4 represents a mast antenna configuration, where the power density is calculated 15 m below the antenna, and the antenna is tilted downwards by 15°. The coordinate system origin (x = 0, y = 0, z = 0) is at the centre of the middle feed model element.

Figure B.29 – Line 4 far-field positions for synthetic model and ray tracing validation example

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a) Normalized horizontal radiation pattern (dB) for θ equal to 0°



b) Normalized vertical radiation pattern (dB) for φ equal to 0° (full blue line) and φ equal to 180°(dashed black line)

Gain = 17,0 dBi and radome length = 2,25 m.

Spherical coordinates φ,θ are defined in B.2.1.

NOTE 1 The file with detailed results can be downloaded from https://www.iec.ch/tc106/supportingdocuments

NOTE 2 The detailed result file includes the normalized horizontal radiation pattern (dB) in 1° steps of φ,θ but uses a different coordinate system.

NOTE 3 If excitation parameters cannot be calculated for the point-source array model or aperture field representation, the weighting coefficients for antenna patches 1 to 9 can be set to 0,582 8; 0,609 7; 0,809 0; 0,949 4; 1,000 0; 0,949 4; 0,809 0; 0,609 7; 0,582 8 respectively, with the relative phase of the applied voltage at each antenna patch set to 0° in order to complete the validation.

Figure B.30 – Antenna parameters for synthetic model and ray tracing algorithms validation example

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Table B.24 – Synthetic model and ray tracing power density reference results

Power density along Figure B.32 line 1		Power density along Figure B.32 line 2		Power density along Figure B.32 line 3		Power density along Figure B.29 line 4	
Position y	S	**Position** x	S	**Position** z	S	**Position** y	S
(m)	(W m^{-2})	(m)	(W m^{-2})	(m)	(W m^{-2})	(m)	(mW m^{-2})
0,5	72,8	0	41,7	0	385	30	2,33
1	41,7	0,2	39,6	0,2	261	40	48,5
1,5	25,5	0,4	34,2	0,4	205	50	105
2	13,1	0,6	27,1	0,6	152	60	80,7
2,5	11,1	0,8	19,8	0,8	80,1	70	45,2
3	11	1	13,3	1	179	80	22,6
3,5	10,7	1,2	8,75	1,2	7,32	90	10,7
4	9,92	1,4	5,76	1,4	1,12	100	4,99

B.7.3 Full wave RF exposure computation

B.7.3.1 Full wave RF field strength / power density computation applicability

Full wave analysis techniques (e.g. methods requiring Maxwell's equations to be solved in all regions of the evaluation space) are essentially used when high accuracy is desired for the evaluation of RF exposure, for example for BS RF field strength, power density or SAR evaluation in source region I (the reactive near-field of the antenna(s)) where ray tracing methods cannot be employed. An accurate and realistic numerical model of the antenna shall be created for a full wave field analysis. Multiple antennas (sources) at multiple frequencies can be modelled.

Full wave methods can also be employed in the source region II (generally radiating near-field) and source region III (generally far-field) but the increase in effort to create an accurate model together with the increase in required computational resources does not necessarily warrant the small increase in accuracy obtained in these regions, compared to ray tracing techniques. Table 7 summarizes recommended (1) and permitted (2 to 4) applications for full wave field evaluations. If any of the full wave techniques are used for analysis in the source region I (generally reactive near-field) with one or more reflectors present inside source region I, then geometrical details of the reflector/reflectors are required to be included in the model.

Full wave analysis in source regions II and III (generally radiating near-field or far-field regions) are permitted. For these scenarios the antennas, and possibly one ground plane, can be included in the full wave analysis. For more environmental reflectors (environment region M), an extended uncertainty analysis is required to take these reflections into account.

B.7.3.2 Full wave RF field strength / power density computation requirements

Computational resources needed to carry out full wave analysis vary greatly with the complexity and size of the structure to be analysed as well as with the analysis method that is chosen. To be able to model an antenna and evaluate the RF field strength or power density at least the following data are required:

a) RF transmitted power;

b) RF transmission system losses;

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c) detailed description of the antenna geometry;

NOTE 1 However, the model can be simplified to reduce the computational cost, e.g. omit unnecessary details which do not influence the results such as the feed network, or approximate an uneven metal plane with variations much smaller than a wavelength with an even plane. Detail such as screws and joints can be omitted and holes much smaller than the wavelength (λ_0/20 of the highest frequency), e.g. screw holes, can be closed. Additionally, dielectric radome structures can typically be omitted in base station antenna simulations.

d) antenna element excitation;

e) antenna mounting height, position and orientation.

Additionally, for verification purposes the following manufacturer data are required:

- antenna gain;
- antenna pattern.

Environment clutter data (ground, buildings) and topography data is required, or shall be accounted for, in the uncertainty analysis/reporting.

Environment data is not required for product compliance assessment, see 6.1, if it is assumed that the antenna is transmitting in free space.

B.7.3.3 Full wave RF field strength / power density computation description

The main methods to use with full wave analysis are the Method of Moments (MoM) [92], [93], [94], [95], [96], the finite element method (FEM) [94], [96], [97], [98] and the finite difference time domain (FDTD) method [92], [96], [98], [99], [100]. These methods are complex and difficult to implement. Nonetheless, various commercial software packages (as well as numerous in-house research codes) are available that can be used for full wave field analysis. Other techniques, such as those used in commercial software packages, are closely related to the three methods mentioned above.

Each of the three main methods has strengths and weaknesses.

When performing full wave field analysis, either with a commercial package or an in-house implementation of any of the three techniques, the following procedure shall be followed.

a) Verify that the evaluation is valid considering the restrictions and limitations of the method.

b) Select commercial code or implement method.

c) Validate 3D code against reference results, see B.7.3.6.

NOTE This applies only to the code developer.

d) Prepare detailed antenna models and verify against measurements for evaluations in source region 1.

e) Perform field evaluation for each antenna.

f) Study convergence for each antenna.

g) Validate converged results against antenna specifications (each antenna).

h) Perform field calculation for all antennas.

i) Perform uncertainty analysis, see B.7.3.5.

j) Use uncertainty analysis for result interpretation, see Clause 9 and Annex G.

k) Prepare evaluation report, see Clause 10.

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B.7.3.4 Implementation of full wave field evaluation

B.7.3.4.1 Method of moments (MoM)

MoM is used to numerically solve integral equation formulations of Maxwell's equations. In principle, the radiated electromagnetic fields are obtained by following a two-step procedure.

- First, structures which are represented with a mesh are replaced by equivalent currents. A matrix is derived which represents the effect of each model element on each other model element and the surface currents are solved.
- Secondly, these currents are integrated to obtain the electric and magnetic fields at the evaluation points.

Metallic structures can be modelled accurately and efficiently using MoM. Fine structures with arbitrary orientations can also be treated easily. Another advantage is that only the radiating antenna needs to be discretized, i.e. the memory requirements and the solution time do not depend on the distance between the source and the field point. For the same reason, there is no uncertainty component arising from the truncation of the computational domain as in the case of FDTD and FEM. MoM is, however, not the most efficient method for inhomogeneous dielectric mediums but when hybridized with FEM it can be an effective solution. Since the typical BS antenna's structure is physically large compared to the wavelength, and with a lot of detail, these simulations can become quite memory- and time-consuming when the frequency is high, e.g. GSM-1800 or UMTS; however, this is a general CEM problem for these calculations.

When using MoM the following principles shall be considered.

a) The edge length of the elements of the model should be small enough to give accurate results and big enough such that realistic computational resources can be used. To determine if the edge lengths of the elements are small enough, convergence tests should be done, which is an iterative process where the mesh size is varied, and the results are compared until the optimal mesh size is determined. The convergence tests should start with edge lengths of, for example, $\lambda_0/5$, $\lambda_0/8$ and $\lambda_0/10$ (with λ_0 the wavelength in free space), and repeat until the results differ by less than 10 %. The edge length of the elements should also be small enough to create a mesh which resembles the geometry. This is sometimes called geometric convergence;

b) When meshing a detailed model of an antenna the mesh elements can be differing lengths: finer (e.g. $\lambda_0/15$) where the highest current variations are, for example close to feed pins, and coarse (e.g. $\lambda_0/8$) elsewhere, to reduce the runtime;

c) In certain cases there are other limits on the size of the mesh elements; for example, if two metal plates are close to each other there are limitations on the maximum edge length of the elements. Another example is the limitations on the radius compared to model element length of a wire element;

d) Accurate information concerning the excitation of each radiating element is required for accurate full wave modelling of an antenna.

B.7.3.4.2 Finite difference time domain (FDTD)

In FDTD, Maxwell's time-dependent curl equations are solved directly by approximating the differential equations with finite difference equivalents over a structured grid. A method called finite integration technique (FIT) is closely related to FDTD and the instructions given here for FDTD also apply for FIT analysis as well.

The computational lattice of FDTD consists of rectangular cells. The difference with MoM is that the computational lattice is extended to all the regions where electric field values are desired to be calculated. This means that the amount of memory in the computer can become a limiting factor for evaluating fields several metres away from the antenna. In traditional FDTD the computational mesh is rectangular in shape. This means that curved surfaces and arbitrarily oriented objects are difficult to model accurately. Furthermore, absorbing boundary conditions have to be applied at the lattice boundaries to simulate open space conditions.

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When FDTD method is used for field evaluation purposes, the following items shall be taken into account.

a) Lattice cell size requirements:

   Local side length of the cell should not exceed one tenth of the wavelength in that material. Otherwise, wave propagation is not accurately simulated.

   Local side length of the cell should be small enough to be able to describe the geometry of the analysed structure. The source region shall be accurately modelled. One weakness of FDTD is that arbitrarily oriented thin sheets usually require a very dense lattice. It is important to be aware of the limitations of sophisticated techniques for modelling fine details, such as conformal meshes and thin wire approximations.

b) Effectiveness of absorbing boundary conditions:

   No ideal absorbing boundary exists and therefore there is always some reflection from the boundary. Typically, absorbing boundary conditions are based on approximate factorization of the wave equation, on extrapolation of field values, or on lossy material layers at the boundary. To be able to estimate the expanded uncertainty of the RF field strength evaluation, the size of the error due to reflections from the lattice boundary shall be quantified. Usually, this means that the simulation has to be repeated with variable lattice sizes and/or absorbing boundary condition parameters.

   To minimize the error due to reflections from lattice boundaries, a useful rule of thumb is that the reflected wave component is small where the incoming wave power density is small. Therefore, it is good to extend the computational lattice especially in the directions where the antenna radiates most.

c) Accurate information concerning the excitation of each radiating element is required for accurate full wave modelling of an antenna.

General requirements and recommended practice for implementing the FDTD methods can be found in IEC/IEEE 62704-1, IEC/IEEE 62704-2, IEC/IEEE 62704-3 (below 6 GHz) and IEC/IEEE 63195-2 (above 6 GHz).

B.7.3.4.3 Finite element method (FEM)

In FEM, the solution for field quantities is approximated with the sum of basis functions that differ from zero in elements of finite size. The elements are chosen to conform to the physical structure to be simulated, which enables easy and accurate modelling of interface and boundary conditions. The mesh is usually created using tetrahedral elements, which allows for accurate geometrical representations of arbitrary structures.

Like FDTD, FEM is also based on volume discretization. As a result, it suffers from the same disadvantage of having to discretize all the regions where field values are to be calculated. However, when the points where field values are to be calculated are outside a minimum domain (with appropriate absorbing boundary conditions) circumscribing the radiating structure, near to near-field transformations similar to those used in the MoM can be employed for those points. The field evaluated on a surface surrounding the radiating structure can be used as a secondary source to evaluate the field outside this surface via integral equations.

When FEM is used for field evaluation purposes, the following items shall be taken into account.

a) Mesh size and/or polynomial order of the basis functions:

   Although adaptive meshing can automatically cope with the accuracy of the solution with a minimum of number of degrees of freedom, it is recommended that the maximum size of the element (side length of the element) be limited to achieve the required accuracy of the field solution. The maximum size of the element in a media should be lower than a fifth or a tenth of wavelength in that medium depending on the polynomial order of the basis functions, second order or first order. For higher order polynomials, the size of the mesh can be relaxed.

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b) Mesh truncation of radiating structures:

In FEM, different techniques to truncate the mesh domain and simulate outgoing waves exist. Very rigorous and thus accurate techniques are those coupling FEM with MoM on an arbitrary surface or coupling FEM with spherical harmonics on a sphere. The surface can be placed close to the radiating surface, minimizing the size of the problem to be solved. A simpler technique like Silver-Muller first order absorbing boundary condition can also be used provided that the truncation surface is far enough away such that the incident wave is close to normal incidence. This distance depends on the radiating structure; a minimum distance of a half wavelength is required. The popular PML (perfectly matched layer) introduced for FDTD has been derived for FEM with the same performance and requirements.

c) Accurate information concerning the excitation of each radiating element is required for accurate full wave modelling of an antenna.

General requirements for implementing FEM methods can be found in IEC/IEEE 62704-4 (below 6 GHz) and IEC/IEEE 63195-2 (above 6 GHz).

B.7.3.5 Full wave RF field strength / power density computation uncertainty

Various parameters shall be taken into account when estimating the expanded uncertainty associated with a full wave field solution. Table B.25 is an uncertainty estimation template, listing uncertainty parameters that shall be considered when using full wave RF field strength or power density analysis.

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Table B.25 – Example template for estimating the expanded uncertainty of a full wave RF field strength / power density computation

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. Coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact. CF	$c^2 \cdot u^2$
System								
Variation in the power of the RF transmitter from its nominal level	dB	rect.		√3	1			
Cable/connector losses	dB	normal		1,96	1			
Mismatch between antenna and its feed	dB	U-shape		√2	1			
Antenna model	dB	normal		1,96	1			
Technique uncertainties								
Including computational assumptions, limitations, interpolation and extrapolation	dB	normal		1,96	1			
Environmental uncertainties								
Scattering from nearby objects and the ground	dB	rect.		√3	1			
Using electric field strength evaluations to estimate magnetic field strength, or vice versa	dB	rect.		√3	1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} (c_i^2 \times u_i^2)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								

NOTE 1 Numerical rounding errors are usually negligible compared to the other listed influence quantities.

NOTE 2 A conservative alternative approach to estimating the standard uncertainty for antenna mismatch is to assume a perfect match.

NOTE 3 See Annex G for guidance on the variables in this table.

NOTE 4 This table is under the assumption that the logarithmic expression of the measured quantities can be similarly treated to that of the linear expression in view of statistical properties.

NOTE 5 The value of divisor δ for normal probability distribution is for 95 % confidence.

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B.7.3.6 Validation of full wave field analyses

B.7.3.6.1 General

B.7.3.6 describes how to validate the correct implementation of full wave field analyses. Before a newly implemented code or commercially available code is used for determining the RF field strengths from BS antennas, it shall be validated for the antenna structure to be analysed.

If the elements of the antenna include dipoles, then validation 1, see B.7.3.6.2, shall be performed.

If the elements of the antenna include slot feeding structure, then validation 2, see B.7.3.6.3, shall be performed.

If the antenna is operating above 6 GHz, then validation 3, see B.7.3.6.4, shall be performed.

Additionally, if the code also is to be used for full wave SAR evaluations, validation using B.7.4.6 shall be performed.

NOTE The mesh size is not explicitly provided for the validation examples because the optimal mesh size can differ across different simulation packages. It is the user's responsibility to verify the chosen mesh size, by conducting convergence tests.

B.7.3.6.2 Validation 1: Antenna with dipole radiators

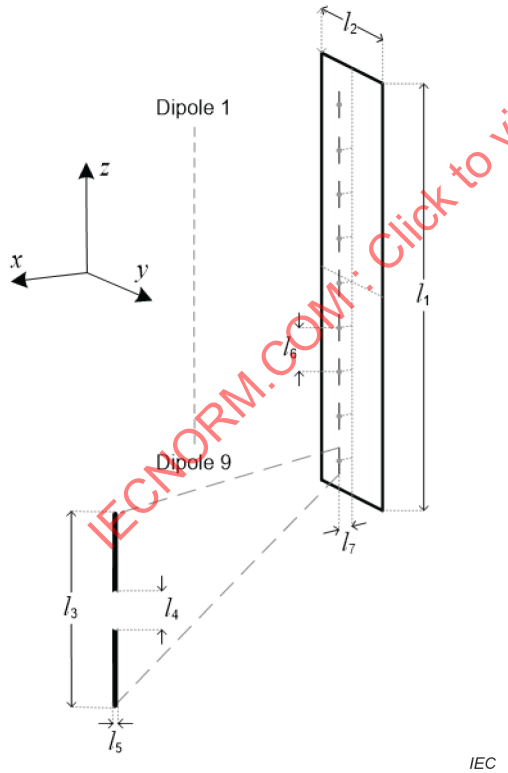
Validation 1 shall use the following procedure.

a) Implement the simple panel BS antenna, representative of a real BS antenna, with dipole radiators and excitation parameters as presented in Figure B.31.

b) The electric field strength values shall be determined along line 1, line 2 and line 3, see Figure B.32, in the near-field of the antenna for a frequency of 900 MHz and P of 80 W.

c) The determined power density values shall be compared with the reference power density values in Table B.26. If the maximum deviation from the reference results is less than 10 %, then the simulation package has passed the validation.

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Dimensions

l_1 Reflector length = 2,25 m

l_2 Reflector width = 0,3 m

l_3 Length of a dipole = 0,158 m

l_4 Separation of feed model elements = 0,02 m

l_5 Dipole thickness = 0,001 m

l_6 Spacing between the dipole centres = 0,25 m

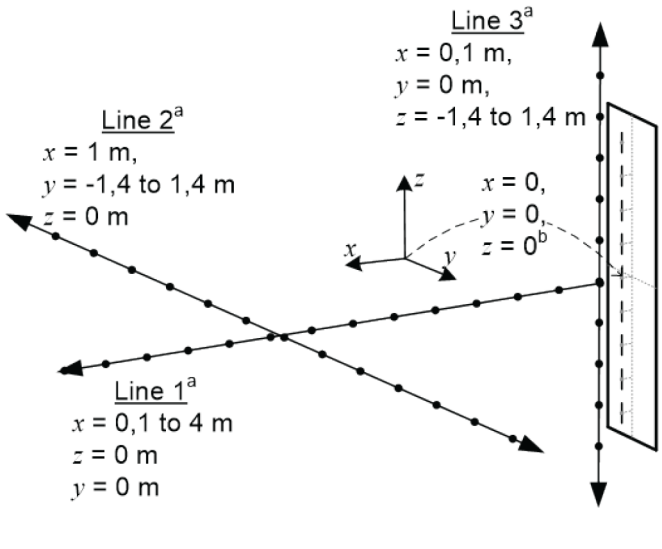
l_7 Spacing between the dipoles and the reflector = 0,04 m

Excitation parameters		
Feed model element	**Amplitude (relative to maximum)**	**Phase (°)**
1 and 9	0,582 8	0
2 and 8	0,609 7	0
3 and 7	0,809 0	0
4 and 6	0,949 4	0
5	1,000 0	0

NOTE 1 The coordinate system origin (x = 0, y = 0, z = 0) is at the centre of the middle feed model element.

NOTE 2 The dipole array is in the centre of the reflector plate if viewed directly from the front.

Figure B.31 – Generic 900 MHz BS antenna with nine dipole radiators



[a] Line 1 is along the x-axis in the main beam direction; line 2 is parallel to the y-axis; line 3 is parallel to the z-axis (i.e. parallel to the antenna).

[b] The coordinate system origin (x = 0, y = 0, z = 0) is at the centre of the middle feed model element.

Figure B.32 – Line 1, 2 and 3 near-field positions for full wave and ray tracing validation

Table B.26 – Validation 1 full wave field reference results

Power density along Figure B.32 line 1		Power density along Figure B.32 line 2		Power density along Figure B.32 line 3	
Position x (m)	S (W m^{-2})	**Position** y (m)	S (W m^{-2})	**Position** z (m)	S (W m^{-2})
0,5	65,8	0	39,4	0	338
1	39,4	±0,2	37,6	±0,2	272
1,5	25	±0,4	32,8	±0,4	163
2	13,4	±0,6	26,3	±0,6	111
2,5	10,7	±0,8	19,6	±0,8	105
3	10,4	±1	13,6	±1	129
3,5	10,1	±1,2	9,16	±1,2	3,77
4	9,44	±1,4	6,22	±1,4	0,173

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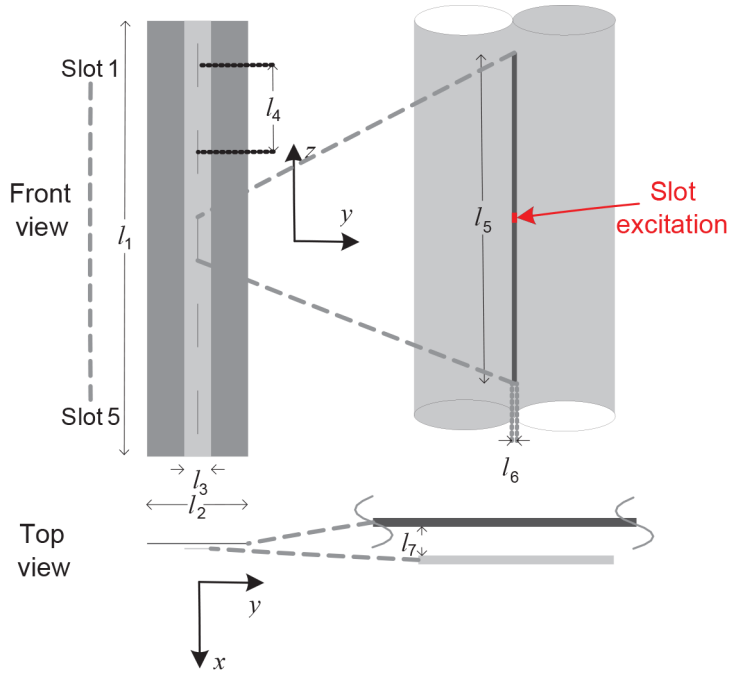
B.7.3.6.3 Validation 2: Antenna with slot elements

Validation 2 shall use the following procedure.

a) Implement the antenna array of five slot radiators as shown in Figure B.33. The antenna is excited with voltage sources in the centres of slots in accordance with the excitation parameters specified in Figure B.33, at a frequency of 1 800 MHz and with P equal to 40 W.

b) The electric field strength values shall be determined along line 1, line 2 and line 3, see Figure B.32, in the near-field of the antenna.

c) The determined power density values shall be compared with the reference power density values in Table B.27. If the maximum deviation from the reference results is less than 10 %, then the simulation package and surveyor have passed the validation.



Dimensions

l_1 reflector/front plate length = 0,66 m

l_2 reflector width = 0,155 m

l_3 front plate width = 0,04 m

l_4 slot centre spacing = 0,32 m

l_5 slot length = 0,067 m

l_6 slot width = 0,002 m

l_7 slot to reflector spacing = 0,007 5 m

Excitation parameters

Feed model element	Amplitude (relative to maximum)	Phase (°)
1 and 5	0,791 7	0
2 and 4	0,878 2	0
3	1	0

NOTE 1 The slots are in the centre of the front plate.

Figure B.33 – Generic 1 800 MHz BS antenna with five slot radiators

Table B.27 – Validation 2 full wave field reference results

Power density along Figure B.32 line 1		Power density along Figure B.32 line 2		Power density along Figure B.32 line 3	
Position x (m)	S (W m^{-2})	Position y (m)	S (W m^{-2})	Position z (m)	S (W m^{-2})
0,5	146	0	90	0	688
1	90	±0,2	79,7	±0,2	477
1,5	50,6	±0,4	57,1	±0,4	20
2	31,1	±0,6	35,5	±0,6	1,31
2,5	20,8	±0,8	20,6	±0,8	0,406
3	14,8	±1	11,8	±1	0,193
3,5	11	±1,2	6,86	±1,2	0,113
4	8,54	±1,4	4,1	±1,4	0,073 9

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B.7.3.6.4 Validation 3: Dipole radiators at 24 GHz

Validation 3 shall use the following procedure.

a) Model three $\lambda/2$-dipoles D1, D2 and D3 operating simultaneously at a frequency of 24 GHz with different amplitudes and phase offsets as described in Annex A of IEC/IEEE 63195-2:2022.

b) The x-, y- and z-vector components of the electric and magnetic fields shall be evaluated on two cubical surfaces with edge lengths of 10,0 mm and 16,0 mm centred about the origin of the reference system as described in Annex A of IEC/IEEE 63195-2:2020.

c) The reference results at these points have been calculated using the Method of Moments and are provided in a file in accordance with the format defined in Annex C of IEC/IEEE 62704-4:2020. The maximum deviation of the E-field strength and H-field strength squared amplitude shall be reported. If the maximum deviation from the reference results is less than 10 %, then the simulation package and surveyor have passed the validation.

B.7.4 Full wave SAR computation

B.7.4.1 Applicability of full wave methods for SAR evaluation

The strength of full wave techniques is that in addition to field evaluation they can also be used to evaluate SAR and therefore enable a comparison to be made with the relevant SAR limit. B.7.3.1 gives information on different methods and their applicability for electromagnetic field evaluation in the near-field region of an antenna. All of the issues discussed in B.7.3.1 shall be considered when performing full wave SAR analysis; this is because it relates to the accurate numerical modelling of the antenna(s) which would serve as the source(s) for full wave SAR calculations. There are additional points to consider for numerical SAR evaluations. These points are described in B.7.4. Table 7 summarizes the applications for full wave SAR evaluations.

B.7.4.2 Full wave SAR computation methods requirements

In addition to the items listed in B.7.3.2, it is necessary to have a phantom or human body model with data on tissue dielectric parameters (permittivity and conductivity applicable to the frequency under investigation) and mass density. Any phantom can be employed for the evaluation, however a full uncertainty analysis, see B.6.2.6, shall be performed.

B.7.4.3 Full wave SAR computation methods description

The most commonly used method for full wave SAR evaluation is the finite difference time domain (FDTD) method ([92], [96], [98], [99], [100]). This method can be used for modelling the source (BS antenna) as discussed in B.7.3.4.2 and is ideal for modelling of the inhomogeneous human body. Both the finite element method (FEM) ([94], [96], [97], [98]) and method of moments (MoM) ([92], [93], [94], [95], [96]), as well as hybrids of these techniques have been used successfully for full wave SAR analysis. Various commercial software packages (and in-house research codes) are available that can be used for full wave SAR analysis.

When performing full wave SAR analysis, either with a commercial package or an in-house implementation of any of the three techniques, the following procedure shall be followed.

a) Verify that the evaluation is valid considering the restrictions and limitations of the method.
b) Select commercial code or implement method.
c) Complete source antenna validation.
d) Validate 3D code against reference results, see B.7.4.6.

NOTE This applies only to the code developer.

e) Prepare detailed antenna models and verify against measurements for evaluations in source region I.
f) Prepare full model with selected phantom.
g) Perform SAR calculations.
h) Study convergence for SAR results.
i) Perform uncertainty analysis, see B.7.4.5.
j) Use uncertainty analysis for result interpretation, see Clause 9 and Annex G.
k) Prepare evaluation report, see Clause 10.

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B.7.4.4 Implementation of full wave SAR evaluation

B.7.4.4.1 General

SAR evaluations involve modelling of the BS antenna as well as the human phantom. B.7.4.4 focuses on the additional requirements for modelling the human phantom.

A human phantom is large compared to the wavelength at the frequencies considered in this document. For this reason, all SAR evaluation simulations are memory- and time-consuming, especially in the upper frequency band (e.g. at UMTS). Simple phantom geometry can be used. Parts of the phantom which are not influencing the results can be omitted. Symmetry can be used to reduce the computational resource requirements when applicable.

If the flat phantoms specified in B.5.2.2 are used in the full-wave SAR evaluation, the corrections factors specified in B.5.3.3 and B.5.3.4 shall be used to determine the maximum local and whole-body SAR.

General requirements and recommended practice for full wave SAR computational methods can be found in IEC/IEEE 62704-1, IEC/IEEE 62704-2, IEC/IEEE 62704-3, IEC/IEEE 62704-4 (below 6 GHz) and IEC/IEEE 63195-2 (above 6 GHz).

B.7.4.4.2 Method of moments (MoM) and hybrid methods

a) When performing SAR calculations using the MoM, the following guidelines shall be adhered to.
   1) The mesh size of the phantoms shall be smaller on the face and in places where the geometry is detailed.
   2) Inhomogeneous dielectric regions can be very resource consuming when simulated with MoM. Hybrid FEM/MoM solutions can be a good alternative for inhomogeneous dielectric regions.
   3) The edge length of the dielectric triangles used to model the phantom shall be small enough to give accurate results and large enough to give a realistic runtime. Suggested mesh sizes for specific situations differ depending on the simulation package. Convergence tests shall be done with the phantom model to ascertain accurate results.

b) When deciding on the mesh size of the phantom, the following principles shall be followed.
   1) To determine if the surface elements of the phantom in a MoM simulation is fine enough, start with three varying edge lengths, e.g. $\lambda_0/5$, $\lambda_0/8$ and $\lambda_0/10$, and do convergence tests with λ_0 the wavelength in free-space.
   2) The dielectric triangles on the surface of the phantom can be meshed as a fraction of λ_0, but any dielectric triangles within the phantom have to be meshed as a fraction of the appropriate λ_r, with λ_r the wavelength in the phantom material.
   3) The tetrahedra of phantoms to be used in hybrid FEM/MoM solutions can be meshed with bigger mesh sizes (up to $\lambda_r/4$). Convergence tests to determine the optimal mesh size shall be performed.
   4) To save computational cost, the phantoms of FEM/MoM hybrid solutions can be enclosed in an air box, which can be meshed coarser (a fraction of λ_0 instead of λ_r). This results in fewer surface elements and therefore in smaller computational requirements.

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B.7.4.4.3 Finite difference time domain (FDTD)

When FDTD method is used for SAR evaluation purposes, the following shall be taken into consideration.

a) When evaluating the whole-body average SAR the local side length of lattice cell shall be smaller or equal to one tenth of the wavelength in the phantom material (λ_r).

b) When evaluating the maximum local SAR (1 g or 10 g), the local side length of lattice cells in the averaging volume (giving the maximum SAR) is recommended to be smaller or equal to one fifteenth of the wavelength in the phantom material (λ_r).

c) The local side length of the lattice cells in the phantom could be smaller on places of high importance, for example where the geometry is detailed or where the highest RF field strengths are likely to occur, and larger on places of less importance.

B.7.4.4.4 Finite element method (FEM)

When performing SAR calculations with FEM, the following guidelines shall be adhered to.

a) The edge length of the tetrahedra used to model the phantom shall be small enough to give accurate results and big enough to give a realistic runtime. Suggested mesh sizes for specific situations differ depending on the simulation package. Convergence tests shall be done with the phantom model to ascertain accurate results.

b) The mesh size of the phantoms shall be smaller on the face and on places where the geometry is detailed.

When deciding on the mesh size of the phantom, the tetrahedra of phantoms to be used in FEM solutions can be meshed with mesh sizes of $\lambda_r/4$, $\lambda_r/5$ and $\lambda_r/8$, with λ_r the wavelength in the phantom material. Perform convergence tests to determine the optimal mesh size.

B.7.4.5 Full wave SAR computation uncertainty

For full wave SAR computation, the uncertainty analysis consists of the uncertainties associated with the source (antenna) modelling as well as the uncertainty parameters associated with the phantom and phantom simulations. Table B.28 presents a list of parameters that shall be recorded, considering information from Clause G.6, Clause G.8, [101] and [102]. Separate SAR uncertainty estimation tables are required for SAR_{wb}, SAR_{10g} (limbs or head/trunk), SAR_{1g} (limbs or head/trunk).

When employing heterogeneous virtual human phantoms, such as the those from the Visible Human Project [103], the corresponding uncertainty information ([61], and [104]) can be used to estimate the expanded uncertainty. If a different phantom is selected, the relevant uncertainty a values shall be determined for that specific phantom.

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Table B.28 – Example template for estimating the expanded uncertainty of a full wave SAR computation

Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact CF	$c^2 \cdot u^2$
System								
Variation in the power of the RF transmitter from its nominal level	dB	rect.		√3	1			
RF transmission system losses	dB	normal		1,96	1			
Mismatch between antenna and its feed	dB	U-shape		√2	1			
Antenna model	dB	normal		1,96	1			
Technique uncertainties								
Analysis technique	dB	normal		1,96	1			
Model resolution (errors associated with finite discretization)	dB	normal		1,96	1			
Interpolations / Extrapolation	dB				1			
Steady state (FDTD)	dB	rect.		√3	1			
For FDTD/FEM: Efficiency of absorbing boundary condition	dB	rect.		√3	1			
For FDTD: Inaccuracy related to truncation of the simulation time	dB	rect.		√3	1			
Environmental uncertainties								
RF propagation – multiple reflections, scatterers and clutter losses	dB	rect.		√3	1			
Uncertainties associated with phantom								
Phantom position and posture	dB				1			
Phantom rotation	dB				1			
Phantom shape and size	dB				1			
Electrical material parameter estimations	dB				1			
Correction factor for homogeneous phantom (if applicable)	dB				1			

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Source of uncertainty (influence quantity)	Unit	Prob. distrib. type	Uncertainty or semi span a	Divisor δ	Sens. coeff. c	Standard uncertainty $u = a/\delta$	Corr. fact CF	$c^2 \cdot u^2$
Uncertainties associated with SAR calculations								
Whole-body and local peak SAR algorithm uncertainties. This could be particularly large for local peak SAR calculations	dB				1			
Errors due to finite discretization of the human phantom model	dB				1			
In the reactive near-field, the errors introduced in the antenna element power division due to the presence of the phantom and the effect thereof on the reactive feed network [105].	dB				1			
Combined correction factor, $CF_c = \sum_{i=1}^{N} CF_i$								N/A
Combined standard uncertainty, $u_c = \sqrt{\sum_{i=1}^{N} (c_i^2 \cdot u_i^2)}$								
Coverage factor for required (e.g. 95 %) confidence interval, k								
Expanded uncertainty, $U = k \cdot u_c$								

NOTE 1 Numerical rounding errors are negligible compared to any of the other uncertainties listed above.

NOTE 2 A conservative alternative approach to estimating the standard uncertainty for antenna mismatch is to assume a perfect match.

NOTE 3 See Annex G for guidance on the variables in this table.

NOTE 4 This table is under the assumption that the logarithmic expression of the measured quantities can be similarly treated to that of the linear expression in view of statistical properties.

NOTE 5 The value of divisor δ for normal probability distribution is for 95 % confidence.

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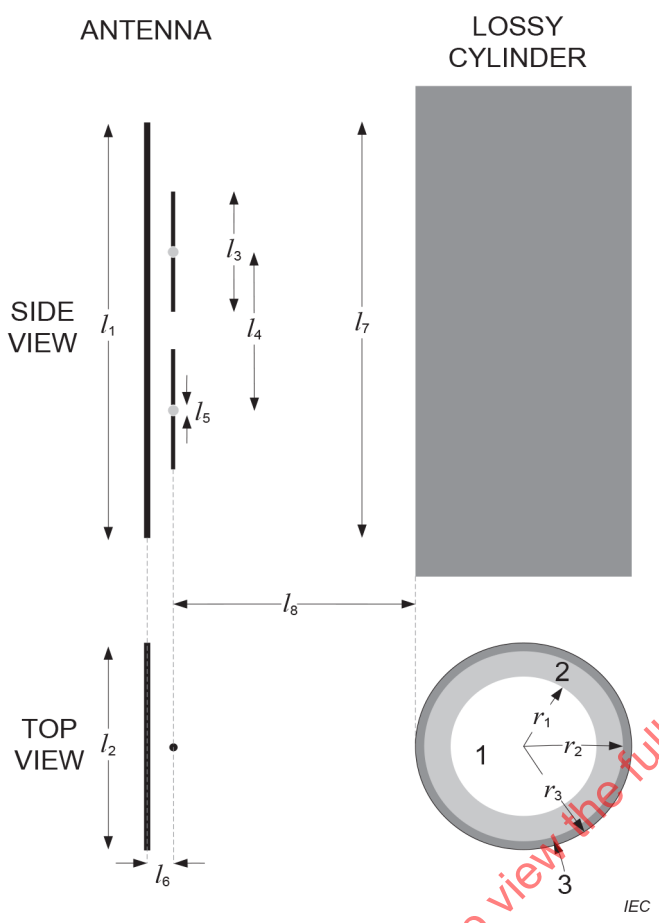
B.7.4.6 Validation of SAR analysis

Figure B.34 shows the validation example consisting of a simplified BS antenna placed in front of a lossy, circular cylinder with three material layers.

The antenna elements are excited by means of a voltage gap (electric field) on each feed model element. Excitation parameters for the dipole array are specified in Figure B.34. The SAR shall be evaluated for a P of 20 W at a frequency of 900 MHz.

Table B.29 presents the validation reference results for whole-body SAR and local SAR (averaged over 10 g of tissue in the shape of a cube).

If the whole-body SAR results are within 3 % of the validation reference results and if the local SAR results are within 15 % of the validation reference results, then the simulation package and surveyor have passed the validation.



Dimensions

l_1 reflector length = 0,6 m

l_2 reflector width = 0,3 m

l_3 dipole length = 0,158 m

l_4 dipole separation = 0,25 m

l_5 antenna feed separation = 0,02 m

l_6 dipole/reflector separation = 0,04 m

l_7 lossy cylinder height = 0,7 m

l_8 dipole/cylinder separation = 0,4 m

r_1 cylinder outer layer 1 radius = 0,138 m

r_2 cylinder outer layer 2 radius = 0,148 m

r_3 cylinder outer radius = 0,15 m

Cylinder material parameters			
Layer	ε_r	σ (S m^{-1})	ρ (kg m^{-3})
1	55,0	0,94	1 041
2	11,3	0,11	916
3	41,4	0,87	1 100

Antenna excitation parameters:

Amplitude (V) (relative) = 1 for both dipoles

Phase (°) (relative) = 0 for both dipoles

NOTE The dipole array is located in the centre of the reflector plate if viewed directly from the front.

Figure B.34 – BS antenna placed in front of a multi-layered lossy cylinder

Table B.29 – Validation reference SAR results for computation method

Metric	Validation reference SAR results for computation method
Whole-body SAR	0,092 W kg^{-1}
Local SAR	1,6 W kg^{-1}

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B.8 Extrapolation from the evaluated values to the maximum or actual values

B.8.1 Extrapolation method

Extrapolation is applicable to exposure evaluation results when the evaluation has been performed in accordance with 6.1, 6.2, or 6.3 at RF power levels lower than the maximum transmitted power. For RF exposure evaluation related to product compliance, it can be used, for example, to extrapolate SAR or power density values to a range of RF transmitted power levels. For RF exposure evaluation related to in-situ RF exposure assessment, extrapolation can be used, for example, to determine the maximum or actual maximum power density or RF field strength values from the measurement of technology-specific stable (i.e. time independent) reference signals (e.g. pilot channels).

The extrapolation shall be performed in accordance with the steps below.

a) Establish the values of the parameters which define the BS configuration as evaluated (the evaluation configuration) and the BS configuration to be assessed (the assessment configuration). If required, consider relevant criteria to define the potential maximum RF field strength case, see B.8.2 and B.8.3. Identify the relevant parameters that affect the RF field strength, power density or SAR including peak-to-average power ratio, see B.5.2.2.3.

b) Establish the case-specific extrapolation factor F_{ext} using all relevant parameters defined in Annex E. Extrapolation can be made to configured maximum or actual maximum exposure conditions.

c) Determine the RF field strength, power density or SAR for the assessment configuration by applying the extrapolation factor F_{ext} to the evaluated RF field strength or power density or SAR as follows using Equation (B.55), Equation (B.56), Equation (B.57), and Equation (B.58):

$$E_{\text{asmt}} = E_{\text{eval}} \cdot \sqrt{F_{\text{ext}}} \tag{B.55}$$

$$H_{\text{asmt}} = H_{\text{eval}} \cdot \sqrt{F_{\text{ext}}} \tag{B.56}$$

$$S_{\text{asmt}} = S_{\text{eval}} \cdot F_{\text{ext}} \tag{B.57}$$

$$\text{SAR}_{\text{asmt}} = \text{SAR}_{\text{eval}} \cdot F_{\text{ext}} \tag{B.58}$$

where

F_{ext} is the extrapolation factor;

E_{asmt} is the assessment electric field strength (V m^{-1});

E_{eval} is the evaluated electric field strength (V m^{-1});

H_{asmt} is the assessment magnetic field strength (A m^{-1});

H_{eval} is the evaluated magnetic field strength (A m^{-1});

S_{asmt} is the assessment power density (W m^{-2});

S_{eval} is the evaluated power density (W m^{-2});

SAR_{asmt} is the assessment SAR (W kg^{-1});

SAR_{eval} is the evaluated SAR (W kg^{-1}).

Depending on the specific technology, the measured RF field strength of a stable reference signal can be used to determine the corresponding RF field strength for the BS in the relevant evaluation condition. For example, such extrapolation can be used to estimate the RF field strength if the BS were to transmit at its maximum output power (i.e. operating at full capacity with all transmit channels engaged at the respective maximum power settings) if that were the requirement for a compliance decision.

If the equipment is able to implement the actual maximum approach specified in 6.2.3 and 8.4, extrapolation shall be performed for the actual maximum RF field strength, SAR, or power density. This shall be considered when deriving the relevant extrapolation factor as described, for instance in Clause E.8.

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NOTE Depending on the technology being evaluated, the following terms "control signal", "synchronization signal", or "broadcast signal" are used to represent a "stable reference signal".

B.8.2 Extrapolation to maximum in-situ RF field strength or power density using broadband measurements

Broadband measurements can be used for extrapolation to the maximum RF field strength, only when the following conditions are satisfied.

a) The EUT transmissions are in a single (known) frequency carrier/channel/band.

b) There are no relevant ambient signals, see B.4.2.6.

c) The EUT parameters at the time of measurement are known (especially the transmitted power).

d) The highest extrapolation factor among all technologies available in the frequency band of the EUT is applied, see B.8.5.2.

e) When evaluating the exposure ratio, if the applicable RF exposure limit is frequency dependent, the lowest exposure limit value for the frequency range of the EUT is applied.

Extrapolation performed under these conditions, results in an overestimation of the maximum RF field strength. The extent of the overestimation should be evaluated and reported.

If the extrapolated result exceeds the exposure limit, it does not necessarily mean that the limits are exceeded. For such a case, extrapolation based on frequency selective measurements should be used to verify compliance with the limit.

If these conditions are not satisfied, broadband measurements should not be used for extrapolation.

B.8.3 Extrapolation to maximum in-situ RF field strength / power density using frequency or code selective measurements

To extrapolate time variant signals to the maximum possible output power conditions, a time invariant component of the signal (e.g. the pilot channel or control channel, see Annex E) shall be evaluated. The ratio between maximum possible signal and the time invariant component of the signal shall be determined based on knowledge of the technology and the specific BS configuration. This ratio shall be used to determine the extrapolation factor. Examples for some common technologies (e.g. TDMA [GSM, TETRA], WCDMA [UMTS] and OFDM [LTE and NR]) are provided in Annex E.

In new technologies like LTE and NR, different signals can be transmitted on different beams. If the radiation pattern of the time-invariant component of the signal (typically a control channel) differs from that of other signals transmitted by the EUT (e.g. traffic channels), the extrapolation factor shall take into account the possible difference in the antenna gain, such that the maximum possible RF field strength is obtained, see B.8.5 and E.8.2.

If it is not possible to isolate the RF field strength from the time invariant part of the signal (e.g. pilot channels – see Annex E), then an approach which overestimates the maximum RF field strength shall apply. It shall be based on the established ratio and assume that the evaluated levels (E_{eval}, H_{eval}, and S_{eval}) are only derived from the invariant part of the signal. The uncertainty due to the measurement and the extrapolation shall be estimated and reported.

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EXAMPLE Consider the case of a GSM BS capable of transmitting simultaneously at 10 W at each of four frequencies including the time invariant component (BCCH), i.e. F_{ext} = 4. Consider the case where at the time of measurement the average (temporal) transmitted power $\overline{P}_{avg}$ was equivalent to 25 W. If the electric field strength of the BCCH can be discriminated, then E_{eval} = E_{BCCH} and E_{asmt} can be accurately determined from E_{asmt} = E_{eval} × 2 or S_{asmt} = S_{eval} × 4. If it was not possible to discriminate the electric field strength from the BCCH $E_{eval} = \sqrt{25/10 \times E_{BCCH}}$, an extrapolation based on from E_{asmt} = E_{eval}× 2 overestimates E_{asmt} by a factor of $\sqrt{25/10}$ The extent of the overestimate is therefore dependent on the ratio $\sqrt{E_{eval}/E_{BCCH}}$. Estimation of the overestimate uncertainty depends on knowledge of the probability distribution in time of $\overline{P}_{avg}$ between, in this case, 10 W and 40 W, i.e. 0 dB to +6 dB assuming no other ambient RF fields.

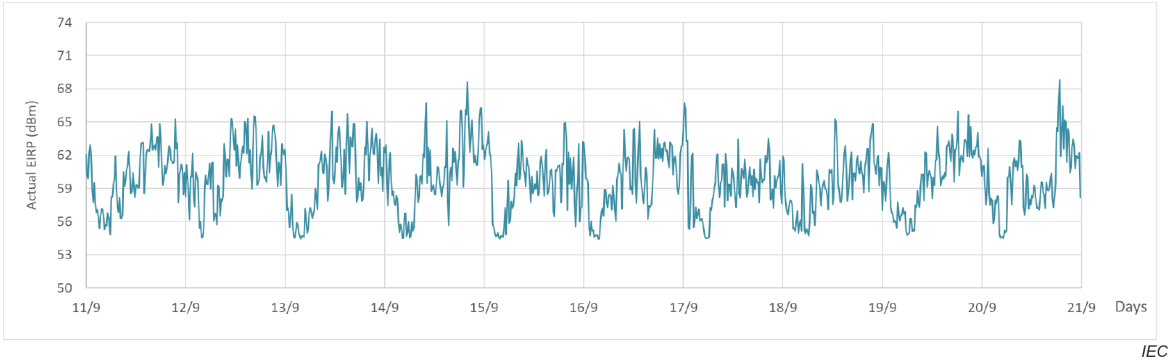
B.8.4 Influence of traffic in real operating network

In many cases, the extrapolation to the configured maximum power or EIRP significantly overestimates the actual exposure, see 6.2.3.1. The actual maximum is generally well below the configured maximum due to access techniques, adaptive power control, discontinuous transmission (DTX) and spatial variation of radiation directions due to massive MIMO or beam steering techniques, see B.8.5.

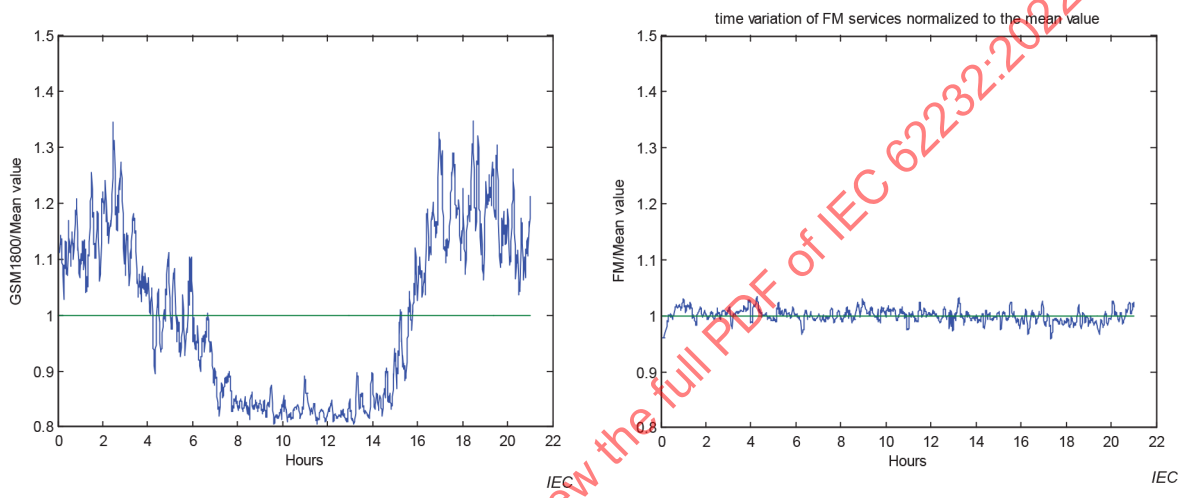
The wireless systems are based on different radio access techniques involving communication techniques such as time division multiple access (TDMA), discontinuous transmission (DTX), code division multiple access (CDMA) and adaptive power control (APC), therefore the power transmitted by the BS is variable. In the case of RF exposure evaluation used for compliance assessment, the measurements or the simulations shall be performed to evaluate the maximum output power level condition, see B.5.1. Nevertheless, these systems rarely transmit at the maximum power.

Figure B.35 shows the time variation of EMF associated with NR, GSM and FM (normalized to the mean value over 24 hours). As can be seen, the FM signal is stable, but the NR and GSM signals are variable. Measurements started at 15:00, the figure shows (as expected) a night exposure smaller than the day exposure, but as can be seen for GSM the difference is below 30 %. The difference between minimum and maximum is less than 2, which is considerably below the theoretical variations (for instance, the ratio is 6 with a mean value of 6 transmitters associated with a "pilot channel"). This is consistent with advanced analysis involving Erlang law, power control and discontinuous transmission.

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a) NR services



b) GSM services

c) FM services

Figure B.35 – Time variation over 24 h of the exposure induced by NR, GSM and FM, each normalized to the mean value

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B.8.5 Extrapolation for massive MIMO and beamforming BS

B.8.5.1 General

In new technologies like LTE-TDD and NR different signals can be transmitted on different beams. The power, gain, steering direction, beam shape and polarization plane of the different beams can vary over time. A stable reference signal, called the broadcast signal, is transmitted independently of the traffic load and user behaviour (e.g. CRS in LTE or SSB in NR BS).

The radiation pattern envelopes for the broadcast and traffic signals should be known for implementing the corresponding extrapolation methods. For the broadcast signal envelope, it is assumed that all resource elements of the complete resource grid transmit the same power as a resource element which is indeed transmitting a part of the broadcast signal.

Extrapolation shall be based on the ratio of the traffic radiation pattern envelope to the broadcast radiation pattern envelope at a given azimuth and elevation angle. This ratio is the extrapolation factor F_{extBeam} at this azimuth and elevation angle. Calculation of the extrapolation factor depends on whether the evaluation location is in line of sight or not. More details are provided in B.8.5.2. If broadcast and traffic radiation pattern envelopes are not available, the extrapolation factor can be estimated by in-situ measurements. Additional information is provided in B.8.5.3.

The extrapolated E-field strength for the assessment configuration is obtained using Equation (B.59). Equivalent expressions can be derived for the magnetic field and for power density.

$$E_{\text{asmt}} = E_{\text{broadcast}} \cdot \sqrt{F_{\text{extBeam}} \cdot F_{\text{BW}} \cdot F_{\text{PR}} \cdot F_{\text{TDC}} \cdot F_{\text{B}}^{-1}} \quad \text{(B.59)}$$

where

E_{asmt} is the extrapolated electric field strength (V m^{-1});

$E_{\text{broadcast}}$ is the evaluated electric field strength (V m^{-1}) per resource element (RE) of the strongest broadcast beam (also called E_{SSB} for NR);

F_{extBeam} is the extrapolation factor corresponding to the ratio of the traffic radiation pattern envelope to the broadcast EIRP envelope in the direction of the evaluation location;

F_{B} is the ratio of the power transmitted for the SSB symbol to the traffic symbol (boosting factor). F_{B} is set to 1 if the power for the SSB and traffic symbols is the same or if the difference in power is already factored in F_{extBeam}.

F_{BW} is the ratio of the total carrier bandwidth and the subcarrier frequency spacing of the broadcast signal;

F_{PR} is the power reduction factor if the actual maximum approach is used, or otherwise is set to 1;

F_{TDC} is the maximum technology duty-cycle factor of all signals.

The value of E_{asmt} is determined assuming the (actual or theoretical) maximum transmitted power, including the contribution from broadcast signals, to be allocated to the traffic beam. Since the antenna EIRP for the broadcast signals is typically well-below the antenna EIRP for the traffic beams, this leads to a conservative estimate of E_{asmt}. In any case, this assumption is not expected to have any significant impact on E_{asmt} as the broadcast signals contribute only to a small amount of the BS maximum transmitted power.

For those unlikely conditions in which the broadcast beam counts for a substantial amount of the power (e.g. above 10 %), extrapolation can be performed separately for traffic and broadcast signals and by subsequently adding their contributions. In this case, the terms in Equation (B.59) should be adjusted accordingly. For example, F_{BW} and F_{TDC} should be determined considering the number of subcarriers and technology duty-cycle factor for broadcast and traffic signals respectively; for broadcast beam F_{extBeam} is equal to 1.

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B.8.5.2 Calculation of the extrapolation factor F_{extBeam}

F_{extBeam} can be calculated as follows depending on the availability of information about azimuth and elevation from the BS to the evaluation location.

a) If the azimuth and elevation from the BS to the evaluation location are known, i.e. BS is in LoS, and the received power of reflected waves is not dominant, the following applies.

   1) F_{extBeam} is selected as the value for that particular azimuth and elevation.

   2) The uncertainty of the evaluation of azimuth and elevation from the evaluation location to the BS shall be taken into account in the total assessment uncertainty.

   3) If the spatial maximum of the broadcast signal in a certain volume around a nominal azimuth and elevation position is used as the base for the extrapolation process, the minimum extrapolation factor F_{extBeam} inside this volume should be used to avoid overestimation.

b) If only a range of azimuth and elevation from the BS to the evaluation location is known, either:

   1) take the maximum value of $F_{extBeam}$ over the range of possible azimuth and elevation angles that includes the evaluation location, which can result in large overestimations if the selected angular region is large compared to the beamwidth; or

   2) take the average value of $F_{extBeam}$ over the range of possible azimuth and elevation angles that includes the PoI, which allows to reduce overestimation;

   and the uncertainty of the evaluation of azimuth and elevation range from the evaluation location to the BS shall be taken into account in the total assessment uncertainty.

c) If the azimuth value and range and the elevation value and range are not known or if the evaluation location is outside the azimuth and elevation range of the BS, $F_{extBeam}$ should be calculated using an alternative method, such as B.8.5.3.

Additional information is provided in Clause E.8.

B.8.5.3 Estimation of the extrapolation factor $F_{extBeam}$

When $F_{extBeam}$ is not available, it can be estimated directly by means of in-situ measurements. The maximum received power density per traffic resource element is measured at the current measurement position over a longer time span. The ratio of this maximum power density per resource element to the power density per resource element of the broadcast signal is used as an estimation of the extrapolation factor $F_{extBeam}$, see for example E.8.2.

This methodology is intended to provide an estimate of $F_{extBeam}$ in normal traffic conditions. Alternatively, traffic can be stimulated by positioning a UE in the same direction as the evaluation location similarly to what is described in B.4.2.5.4.

When $F_{extBeam}$ is estimated by means of in-situ measurements, it already includes possible differences in the power transmitted for broadcast and traffic symbols (i.e. F_B = 1).

If $F_{extBeam}$ evaluation is based on in-situ measurements, see for example E.8.2.1.4, the measured value inherently includes the effective extrapolation factor $F_{extBeamEff}$ introduced in B.8.5.2.

If the BS is in a non-line-of-sight (NLoS) or scattering environment, the extrapolation factor derived from the nominal gain of broadcast and traffic beams (i.e. LoS) can overestimate RF exposure due to reflected waves [63]. In such conditions, the effective gain of the antenna [64] can be used because it provides a better estimate of the propagation channel. The concept of effective extrapolation factor $F_{extBeamEff}$, i.e. the extrapolation factor derived from the effective gain approach, has been introduced in [63]. The evaluation of $F_{extBeamEff}$ can be done using detailed channel modelling tools as well as a simplified calculation process described in [63]. These methods can be implemented to improve the accuracy of extrapolation in case of beamforming.

NOTE If in situ measurements are used to determine $F_{extBeam}$, then effectively the maximum received power density per traffic resource element provides directly the value of $E_{broadcast} \cdot \sqrt{F_{extBeam}}$.

B.8.6 Maximum exposure extrapolation with dynamic spectrum sharing (DSS)

The principle of dynamic spectrum sharing (DSS) is that two technologies, e.g. LTE and NR, are sharing the same frequency band. The amount of resources scheduled to NR or LTE is not static but it is varying dynamically (e.g. on a 1 ms basis) depending on the traffic needs. The reference signals of each technology are transmitted by the BS. Therefore, the extrapolation methods described in each technology still apply; see, for example, Clause E.7 for LTE and Clause E.8 for NR.

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The extrapolated exposure level with DSS is the maximum value among all extrapolated levels for each individual technology. If the broadcast signal contributes significantly to the total power (e.g. above 10 %), extrapolation should be performed separately for traffic and broadcast signals as indicated in B.8.5.2.

B.9 Guidance for implementing the actual maximum approach

B.9.1 BS actual EIRP evaluation assumptions

During antenna system operations, the antenna gain, beam direction and transmitted power are varying in time, azimuth and elevation. The actual EIRP is averaged over T_{avg_act} and depends on deterministic factors (P_{TXM}, F_{TDC} and G_{MLB}) and factors (F_{PDL} and F_G) which can be deterministic for BS using fixed beams or variable in azimuth and elevation for BS using steerable beams such as mMIMO.

The actual EIRP is calculated using Equation (B.60).

$$\mathrm{EIRP}_{act}(\varphi,\theta) = P_{TXM} \cdot F_{TDC} \cdot G_{MLB} \cdot F_{PDL}(\varphi,\theta) \cdot F_G(\varphi,\theta) \quad \text{(B.60)}$$

where

φ is the azimuth;

θ is the elevation;

$\mathrm{EIRP}_{act}(\varphi,\theta)$ is the actual value of the transmitted EIRP (per sector, cell or segment);

P_{TXM} is the maximum transmitted power configured in downlink (deterministic factor);

F_{TDC} is the technology duty-cycle factor of the signal (deterministic factor);

G_{MLB} is the maximum gain in the main lobe for fixed beam or boresight for steerable beams (deterministic factor);

$F_{PDL}(\varphi,\theta)$ is the variable part of the downlink transmitted power $F_{PDL}(\varphi,\theta,t)$ averaged on the time interval T_{avg_act} and normalized to one (i.e. takes a maximum value of one and has no unit);

$F_G(\varphi,\theta)$ is the variable part of the gain $F_G(\varphi,\theta,t)$ averaged on the time interval T_{avg_act} and normalized to one;

t is time;

T_{avg_act} is the time interval used for time averaging.

The variable factors are represented by the normalized EIRP factor as described in Equation (B.61).

$$F_{EIRP}(\varphi,\theta) = F_{PDL}(\varphi,\theta) \cdot F_G(\varphi,\theta) \quad \text{(B.61)}$$

The power reduction factor F_{PR} can be derived from the statistical analysis (CDF) of the actual transmitted power or EIRP, see 6.2.3, and does not include deterministic factors such as the technology duty-cycle factor (F_{TDC}, see B.9.1). The actual maximum transmitted power is derived from the maximum transmitted power (generally corresponding to the configured maximum transmitted power if there is no feeder loss) using Equation (B.62).

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$$P_{TXAM} = P_{TXM} \cdot F_{TDC} \cdot F_{PR} \quad \text{(B.62)}$$

where

P_{TXAM} is the actual maximum transmitted power;

P_{TXM} is the maximum transmitted power configured in downlink (deterministic factor);

F_{TDC} is the technology duty-cycle factor;

F_{PR} is the power reduction factor.

Consistently, the actual maximum transmitted EIRP (per sector, cell or segment) is derived from the configured maximum transmitted EIRP using Equation (B.63).

$$EIRP_{TXAM} = P_{TXM} \cdot F_{TDC} \cdot G_{MLB} \cdot F_{PR} \quad \text{(B.63)}$$

where

$EIRP_{TXAM}$ is the actual maximum transmitted EIRP (per sector, cell or segment);

P_{TXM} is the maximum transmitted power configured in downlink (deterministic factor);

F_{TDC} is the technology duty-cycle factor;

G_{MLB} is the maximum gain in the main lobe for fixed beam or boresight for steerable beams (deterministic factor);

F_{PR} is the power reduction factor (per sector, cell or segment).

B.9.2 Technology duty-cycle factor description

The BS technology duty-cycle factor F_{TDC} depends on both the mobile technology being used (GSM, UMTS, LTE-TDD, LTE-FDD or NR) and on the network operator's implementation of the technology.

Figure B.36 represents a generic structure of a frame, showing multiple transmission periods (marked Tx ON) in a frame and periods when there is no transmission because the BS is either in receiving mode (in TDD) or it corresponds to guard time between operation modes. P_{TXM} is the maximum transmitted power of the BS when the transmitter is ON, i.e. during time interval T_{TXi}. More accurate figures can be derived from specifications 3GPP TS 36.211 [18] for LTE and 3GPP TS 38.211 [19] for NR. Figure E.8 and Figure E.9 also provide indications for LTE-FDD and LTE-TDD, respectively.

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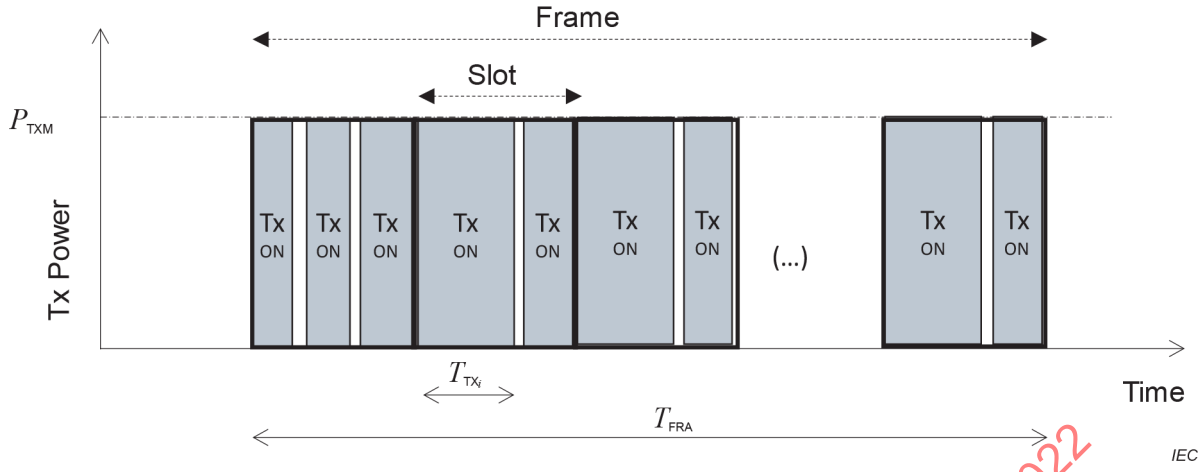


Figure B.36– Generic structure of a base station transmitted RF signal frame

The general formula for F_{TDC} is given in Equation (B.64):

$$F_{TDC} = \frac{\sum_{i}^{Frame} T_{TXi}}{T_{FRA}} \quad \text{(B.64)}$$

where

F_{TDC} is the technology duty-cycle factor;

T_{TXi} is the duration of the i-th interval of transmitted signal in the frame;

T_{FRA} is the duration of a frame.

For GSM and UMTS mobile technologies, the default value for F_{TDC} is 1.

For LTE and NR mobile technologies, the transmission (Tx) periods are used to convey the signal to users (PDSCH) but also downlink control channel (PDCCH), broadcast channel (PBCH) and reference signals used for synchronization purposes. More details can be found in 3GPP TS 36.211 [18] for LTE and 3GPP TS 38.211 [19] for NR.

For LTE-FDD and NR-FDD, the approximated value of F_{TDC} is 1.

For LTE-TDD and NR-TDD, the approximated value of F_{TDC} is provided by Equation (B.65).

$$F_{TDC} \approx \frac{T_{DL}}{T_{DL} + T_{UL}} \quad \text{(B.65)}$$

where

T_{DL} is the total duration of the downlink signal per frame;

T_{UL} is the total duration of the time period used for uplink per frame.

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For example, for TDD Configuration 2 described in Table E.9 there is one uplink (UL) time period for three downlink (DL) periods, resulting in a duty-cycle factor of 75 %. Typical values of F_{TDC} are between 0,75 and 0,8 depending on the special subframe format implemented. When the exact value is not specified, an approximated value of 0,75 (i.e. 3/(3+1)) can be chosen using Equation (B.65) approximation.

B.9.3 CDF evaluation using modelling studies

B.9.3.1 Guiding principles

This describes the approach to be used when the CDF considered in the implementation of the actual maximum approach is derived from modelling studies, see 6.2.3.2. When performing such modelling studies on BS using mMIMO, the number, position, duration of service, and movement of each user are all relevant statistical factors. These factors influence the actual power or EIRP per beam during an actual time-averaging period T_{avg_act}. The spatial distribution of UEs and traffic generation follows scenarios that can be derived from 3GPP standards such as [63], [106], [107] or dedicated papers [31], [32] or [34].

The main evaluation steps for performing modelling studies are:

a) define the set of parameters relevant to conduct traffic modelling and RF exposure assessment of a mMIMO site or site cluster for a given mobile system technology;

b) evaluate the statistical distribution of the transmitted power or EIRP, and derive the actual maximum transmitted power or EIRP;

c) derive the actual maximum RF exposure and the corresponding RF compliance boundary.

B.9.3.2 Simulation model parameters

Usual parameters for conducting an RF exposure calculation in accordance with Clause B.6 need to be complemented by new parameters defining the realistic operation of the base station site or site cluster. Table B.30 provides an example of the simulation parameters generally used for statistical analysis.

Table B.30 – Relevant parameters for performing RF exposure modelling studies of a massive MIMO site or site cluster

Type	Simulation model parameters	Example(s)
General	Technology	NR TDD or LTE-TDD
	Technology duty-cycle factor	0,75
	Use case	Mobile broadband
	Environment type	Urban or sub-urban or rural
	Frequency	3,5 GHz (3GPP Band 42) or 2,6 GHz (3GPP Band 38)
Site	Installation height	10 m
	Number of sectors per site	1 or 3
Site cluster	Number of sites	1 or 7
	Cell shape	Hexagonal
Antenna	Type	2D array antenna with 32 cross polarized radiating elements: 4 columns × 8 rows
	Dimension of the array antenna panel	30 cm × 60 cm
	Maximum gain in the main lobe	24 dBi
	Horizontal half-power beamwidth (H-HPBW)	12,3°
	Vertical half-power beamwidth (V-HPBW)	8,1°
	Beam steering range (azimuth)	90°

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Type	Simulation model parameters	Example(s)
	Beam steering range (elevation)	40°
Radiating element	Gain	8 dBi
	Horizontal half-power beamwidth (H-HPBW)	70°
	Vertical half-power beamwidth (V-HPBW)	70°
Equipment transmitter	Rated maximum transmitted power	100 W (50 dBm)
	Rated maximum transmitted EIRP	74 dBm
System simulations	Beamforming type	Grid of beam
	Channel model / traffic load	Full buffer / 100 %
	Number of simultaneously served UEs	1 or 5 or more
	UE spatial distribution law	Normal
	UE indoor/outdoor ratio	80 % indoor, 20 % outdoor
	UE service duration	30 s
	Model operation duration[a]	
	Time averaging period[b]	6 min
	Contributions from all beams	Included

[a] Model operation duration is not the simulation processing time; rather, it is the time interval used to model the realistic operation of the BS.

[b] The time-averaging period recommended by RF exposure limits is frequency dependent and decreases in the millimetre wave frequency range. For example, in ICNIRP-1998 [2], the recommended time-averaging period is 6 min up to 10 GHz and then decreases using the following formula: $68/f^{1,05}$ min period (where f is the frequency in GHz).

Examples of modelling case studies of BS using mMIMO antennas are provided in IEC TR 62669 [5] and Clause E.10.

B.9.4 CDF evaluation using measurement studies on operational BS sites

B.9.4.1 Guiding principles

The actual maximum transmitted power for BS can be established using measurement studies, see 6.2.3.2. Due to the high variability of the transmitted signal in azimuth, elevation and time, statistical analysis of the transmission parameters of the base station is recommended. In accordance with B.8.1, actual maximum transmitted power or EIRP can be obtained from network-based measurements, gathering information from either a single cell, or a cluster of cells deployed across a large geographical area and performing a statistical analysis.

The general process to conduct experimental studies on mMIMO site or site cluster is as follows.

a) Define the investigation area, the list of relevant transmitters impacting RF exposure and their parameters, including the key system parameters for the technology or technologies under investigation(s).

b) Perform network-based measurements using BS counters of relevance for the RF exposure assessments, see B.9.5. This includes azimuth, elevation, time and in-situ RF exposure measurements, provided the purpose of the statistical analysis is to extrapolate field measurements to the actual maximum transmitted power.

c) Derive statistical distribution of the transmitted power or EIRP and evaluate the actual maximum RF exposure parameters within the investigation area.

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B.9.4.2 Measurement campaign parameters

Before starting RF exposure measurements in the vicinity of a BS site or site cluster, it is recommended to collect general information that can impact the outcome of the RF exposure assessment. Table B.31 provides the relevant parameters. Implementation examples are provided in IEC TR 62669 [5].

Table B.31 – Measurement campaign parameters for performing RF exposure assessment of a massive MIMO site or site cluster

Type	Measurement campaign parameters	Example(s)
General	Investigation purpose	General public exposure or occupational exposure or validation of modelling studies or other
	Investigation area	Geographical description of the area under investigation
	Investigation time	From Day1 to Day2
	Technology or technologies under investigation	LTE-TDD / NR
	Technology use case	Mobile broadband
	Environment type	Urban or sub-urban
Per technology	Technology	NR TDD
	Technology duty-cycle factor	0,75
	Frequency	3,5 GHz (3GPP Band 42)
	Number of sites in the experiment	1
Per site/cluster	Address	Street, City, Country
	Position (GPS or equivalent)	N:48.812476; E2.361383
	Installation height	10 m
	Number and azimuth of sectors (cells) per technology/frequency	
Per antenna	Type	2D array antenna with 32 cross polarized radiating elements: 4 columns × 8 rows
	Dimension	30 cm × 60 cm
	Maximum gain in the main lobe	24 dBi
	Horizontal half-power beamwidth (H-HPBW)	12° (at 3 dB)
	Vertical half-power beamwidth (V-HPBW)	8° (at 3 dB)
	Beam steering range (azimuth)	90° (at 3 dB)
	Beam steering range (elevation)	40° (at 3 dB)
	RF compliance boundary	In accordance with IEC 62232
Equipment transmitter	Rated maximum transmitted power	100 W (50 dBm)
	Rated maximum transmitted EIRP	74 dBm
RF exposure	RF exposure modelling on the investigation area (if available)	In accordance with IEC 62232
	Field measurement types	In-situ, Case A and/or Case B
	Measurement equipment	Equipment name, frequency range, accuracy, etc.
	Base station counters	Actual DL transmitted power or EIRP per cell or cell segment, connected users per cell, etc.
	Counter time-averaging period	15 min
	Specific requirements	For example, indicate here if a process was used to verify that there is communication in the direction of the evaluation location

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B.9.4.3 Experiment process

The experimental process consists of performing the RF exposure assessment in the investigation area as specified in 6.3. In parallel, base station counters as specified in B.9.5 are collected in order to assess impact of time variations due to traffic load on RF exposure or provide other relevant information for consistency checks.

For the case where the purpose of the RF assessment is to evaluate the maximum RF exposure conditions taking into account traffic and transmitted power variations, derive the actual maximum RF exposure from counter data and the CDF of transmitted power during the measurement period, see B.9.5.

B.9.5 Actual transmitted power or EIRP monitoring counters

The following counters are relevant for the implementation of the actual maximum approach specified in 6.2.3 and 8.4:

a) total actual transmitted power or EIRP in downlink;

b) for massive MIMO and beam steering antennas, P_{act} or $EIRP_{act}$ per segment, see Figure 19. These counters monitor the actual transmitted power or EIRP within each segment defined by an azimuth and elevation aperture range; some post-processing is sometimes needed to obtain the power in the segments;

c) in addition, total actual transmitted power or EIRP per beam including all signals (PDSCH, CSI-RS, SSB, etc.) on each beam used in the configured beam-set, when applicable, for example for massive MIMO or beam steering antennas using GoB.

Guidance for the validation of monitoring counters is provided in Annex C.

The counter reporting time interval T_{rep} is the period of counter reporting by the network management system (NMS). T_{rep} is typically 15 min, although 5 min is possible for some vendors. It can be different from the actual averaging time used for the calculation of counters T_{avg_act}. Both T_{rep} and T_{avg_act} shall be reported.

NOTE Counter naming can differ between BS manufacturers.

When conducting statistical analysis on operational networks, it is important that the period is representative of the variability of operations, e.g. considering load variations within a day or a week or other seasonal effects in touristic areas, etc. To obtain statistically relevant results, it is recommended to collect data for a sufficiently long period of time, for example one week per configuration type.

B.9.6 Configurations with multiple transmitters

In certain situations, RF exposure is generated by multiple independent transmitters in the same area, for example multiple network operators and/or transmitters around the evaluation location operating on multiple frequencies with different azimuth. The probability that these multiple independent transmitter systems are delivering the actual maximum RF exposure on the same point synchronously at the same time period is lower than for one single transmitter. The rationale and background are provided in IEC TR 62669 [5].

For such situations, the power combination factor can be applied to the actual maximum transmitted power and other relevant percentiles, see [108] and [109], using Equation (B.66):

$$P_{TXAM} = P_{TXM} \cdot F_{TDC} \cdot F_{PR} \cdot F_{PC} \quad \text{(B.66)}$$

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where

P_{TXAM} is the actual maximum transmitted power;

P_{TXM} is the maximum transmitted power configured in downlink (deterministic factor);

F_{TDC} is the technology duty-cycle factor;

F_{PR} is the power reduction factor;

F_{PC} is the power combination factor.

The value of F_{PC} is equal to 1 if the assumption of multiple independent transmitters does not apply, for example if all transmitters on the site have synchronized load variations. Examples of power combination factors are provided in Table B.32.

However, there are other situations for which the above-mentioned assumption does not apply and where the actual maximum RF exposure at the evaluation location can be considered to be generated synchronously by all transmitters during operation. This restriction applies, for example, to areas with multiple transmitters and where high capacity and data throughput is delivered in a confined space, e.g. in a crowded sports stadium.

One important assumption in the assessment of power combination factors in Table B.32 is that all transmitters have the same maximum transmitted power, i.e. the same weight in the statistical combination. If the maximum transmitted power is not the same or if the frequency band is not the same, the weighting in the statistical combination shall be adapted to take into account the different maximum transmitted powers or/and the relevant reference levels.

Table B.32 – Power combination factors applicable to the normalized actual transmitted power CDF in case of combination of multiple independent identical transmitters

Number of transmitters	Power combination factors for each percentile					
	5 %	25 %	50 %	75 %	95 %	99 %
1 transmitter (reference)	1,00	1,00	1,00	1,00	1,00	1,00
2 transmitters	1,91	1,30	1,08	0,94	0,82	0,77
3 transmitters	2,46	1,43	1,11	0,91	0,75	0,68
4 transmitters	2,82	1,50	1,12	0,89	0,71	0,63
5 transmitters	3,05	1,55	1,13	0,87	0,67	0,60

Assuming that the combination applies to two independent signals having the same CDF, where one signal is equal to a ratio p of the other, the combination factors can be adjusted as shown in Table B.33. The value with p = 1 corresponds to the power combination factor from Table B.32.

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Table B.33 – Power combination factors applicable to two independent transmitters with a ratio p in amplitude

Ratio p between two independent transmitters	Power combination factors for each percentile					
	5 %	25 %	50 %	75 %	95 %	99 %
0,1	1,34	1,09	1,01	0,98	0,95	0,95
0,2	1,55	1,15	1,03	0,96	0,91	0,90
0,3	1,68	1,20	1,04	0,95	0,89	0,86
0,4	1,77	1,24	1,06	0,95	0,87	0,83
0,5	1,81	1,26	1,06	0,94	0,85	0,81
0,6	1,85	1,27	1,07	0,94	0,84	0,80
0,7	1,87	1,28	1,07	0,94	0,83	0,79
0,8	1,88	1,29	1,07	0,94	0,83	0,78
0,9	1,89	1,29	1,08	0,94	0,82	0,78
1	1,91	1,30	1,08	0,94	0,82	0,77

B.10 Transmitted power or EIRP evaluation

B.10.1 General

BS parameters, such as BS transmitted power and EIRP are used for implementation of RF exposure assessment methods described in this document. When performing direct measurements of these parameters, it is recommended to follow the procedures specified by international standardization bodies, such as 3GPP TS 38.141-1 [42] and 3GPP TS 38.141-2 [43] for NR, see 8.6. The evaluation methods described in Clause B.10 provide complementary information especially relevant for the validation of power or EIRP control features and monitoring counter(s) as described in Annex C.

B.10.2 Measurement of the transmitted power in conducted mode

General guidelines can be found in 3GPP recommendations, such as 3GPP TS 38.141-1 for NR [42]. The test setup is shown in Figure B.37. It consists of a calibrated directional coupler placed between the output port of the BS and the input port of the antenna. The "forward" port of the directional coupler is connected to a calibrated power meter. A directional coupler with an adequate coupling factor level (e.g. 20 dB) should be used to limit the influence on the output power to the antenna.

When the antenna is matched to the characteristic impedance of the feeding line, it can be removed from the test setup with the output/transmitted port of the directional coupler terminated in a matched load. For antennas not matched to the characteristic impedance of the feeding line, mismatching of the antenna should be included in the uncertainty budget.

If required, an attenuator can be connected to the output of the BS to protect the directional coupler and to the forward port of the directional coupler to protect the power meter. Additionally, a matched load is connected to the reflected port of the directional coupler.

An example test procedure is described in C.3.1.

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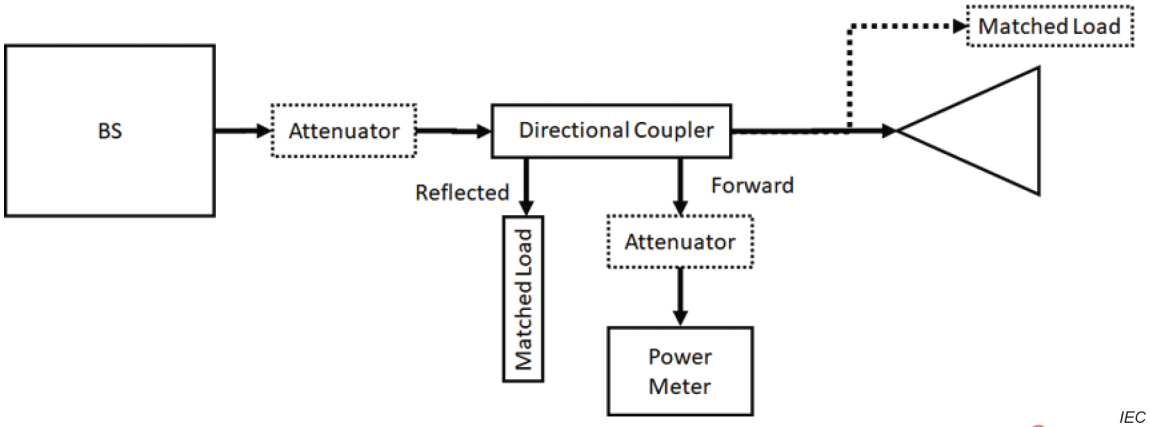


Figure B.37 – Example of setup for the direct power level measurement for BS equipped with direct access conducted output ports

B.10.3 Measurement of the transmitted power in OTA conditions

General guidelines can be found in 3GPP recommendations, such as 3GPP 38.141-2 [43] for NR.

The test setup consists of an anechoic chamber equipped with a measurement system able to perform power density measurements over the entire sphere or a major portion of the sphere covering at least the angular region where the radiation pattern is within 20 dB of the peak value. The measurement system gives, as an output, the integration of the power density over the sphere or measured portion of the sphere, resulting in the transmitted power.

An example of implementation is described in C.3.2.

B.10.4 Measurement of the EIRP in OTA and laboratory conditions

General guidelines can be found in 3GPP recommendations, such as 3GPP 38.141-2 [43] for NR.

The BS should be installed in a shielded laboratory environment, preferably an anechoic chamber for OTA validation, and normal laboratory conditions for conducted mode measurements. The transmission of the BS should be controlled either using dedicated traffic load generation software or by connecting a user equipment (UE) with software that makes it possible to demand different levels of transmission.

The RF EMF exposure should be evaluated using RF field strength and power density measurement methodology specified in 8.2.2 and Clause B.4. With the test BS being the only RF source in the laboratory, either broadband or frequency selective measurement equipment can be used. The distance between the BS and the probe should be established so that the beams are fully formed at the measurement probe location. Personnel should not be present in the test chamber during the measurement.

In the case of TDD and where the receiver is not locked on the downlink, if a UE is used to generate the downlink transmission, it should be placed at least 1,5 m away from the probe or there should be absorbing material between the probe and the UE such that the uplink contribution to the RF EMF exposure can be neglected as described in B.4.2.5.4.1. It is not required to take distance between the UE and the probe into account if a download only transmission mode is implemented or if the measurement techniques allow to separate uplink and downlink exposure contributions, see for example E.8.2.1.3.

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The probe should be placed near the boresight direction of the antenna, and if possible, in the far-field. The output power level of the BS should be selected to obtain an RF EMF level within the measurement range of the RF EMF measurement equipment. In case the BS applies beam steering, and the feature is controlling the power per beam or angular segment, the UE and the probe should be aligned with the BS.

An example test procedure is described in C.3.3.2.

B.10.5 Measurement of the EIRP in OTA and in-situ conditions

The transmission of the BS should be controlled either using dedicated traffic load generation software or by connecting one or more UE with software that makes it possible to demand different levels of transmission.

Measurements of the RF EMF exposure should be performed using methodology provided in 6.3. Frequency selective measurement equipment should be used such that only the transmission from the test BS is included.

To avoid that the environment has a significant impact on the results, the EMF measurement equipment should preferably be placed in an open area with line-of-sight to the BS antenna. During the measurements people should not be allowed to move in the area around the probe. If a UE is used to generate the downlink transmission and in the case of TDD, it should be placed at least 1,5 m away from the probe such that the uplink contribution to the RF EMF exposure is negligible as described in B.4.2.5.4.1. It is not required to take distance between the UE and the probe into account if a download only transmission mode is implemented or if the measurement techniques allow to separate uplink and downlink exposure contributions, see for example E.8.2.1.3.

Movements near the UE should also be avoided. If the BS applies beam steering, the probe should be placed within the steering range of the antenna, preferably close to the boresight direction, and if a UE is used it should be aligned with the probe in the direction of the antenna.

An example test procedure is described C.3.4.2.

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Annex C
(informative)

Guidelines for the validation of power or EIRP control features and monitoring counter(s) related to the actual maximum approach

C.1 Overview

When implementing the actual maximum approach as specified in 6.2.3, 8.4 and Clause B.9, the BS actual maximum power or EIRP should not exceed the actual maximum threshold value during its operation. This Annex C provides guidance for the validation of actual power or EIRP monitoring counters and control tools related to the actual maximum approach, and also establishes minimum reporting recommendations. The validation processes are based on evaluation methods described Annex B including the test setup described in Clause B.10. Additionally, a few detailed case studies have been included as implementation examples.

The actual maximum approach is based on assessing RF exposure compliance using the actual maximum transmitted power or EIRP of the BS. Hence, appropriate actual power or EIRP monitoring counters and/or control features should be implemented such that RF exposure compliance, based on the configured actual transmitted power or EIRP thresholds, is maintained.

Ensuring that the actual power or EIRP monitoring counters and/or control features operate accurately and reliably is an important factor for BS vendors, network operators and regulatory bodies.

C.2 Guidelines for validating control feature(s) and monitoring counters

The principle for validating power or EIRP monitoring counters is to set up known BS transmitted parameters, measure the resulting exposure parameters and compare them to the same exposure parameters derived from the power or EIRP counters. The correlation between the power or EIRP counter, the configured maximum power on the radio and the transmitted power or EIRP provides confidence in the implementation of the actual maximum approach. The actual maximum approach can involve the determination of the CDF from actual transmitted power or EIRP counters in order to obtain the value of the power reduction factor F_{PR} in Equation (B.62), corresponding to the selected percentile of the CDF.

The principle for validating power or EIRP control features is to configure a power reduction factor and check that the actual transmitted power or EIRP does not exceed the configured actual maximum threshold regardless of the traffic load conditions on the BS. This verification can be performed either by measurement or by using counters. It is recommended that the control feature validation test is preceded by a monitoring counter validation test if counters are used for the validation of the control feature.

The monitoring counter and control feature validation can be performed either in conducted mode using a power meter or over-the-air (OTA) using E-field strength measurements. It is recommended to use:

a) conducted mode validation for a BS with accessible ports to an external antenna and fixed beam, see C.3.1; or

b) OTA validation for a BS with an active antenna system (i.e. no accessible port) or a BS with accessible ports using beam steering (e.g. 8T8R BS), see C.3.2 and C.3.3.

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C.3 Validation of power or EIRP monitoring counter in laboratory conditions

C.3.1 Validation of power or EIRP monitoring counter in conducted mode – test procedure

C.3.1.1 General

The test setup described in B.10.2 can be used. For such BS with external antenna and fixed gain (e.g. no beam steering), the total transmitted power and EIRP are typically proportional. It is expected that the power counter is used for validation in conducted mode. However, if the EIRP counter is available, it can also be used taking into consideration the antenna gain.

The BS is set to generate the configured transmitted power, continuously, full buffer, by features that can be internal or external to the BS. Moreover, the power counter is set to the selected actual averaging time (for example 360 s) and then activated. The recommended procedure consists of the steps described in C.3.1.2 to C.3.1.5.

C.3.1.2 Step 1 – Counter validation at the rated maximum power and determination of the reference power

The BS is activated at the rated maximum power using full buffer traffic load, for a period larger than the actual averaging time T_{avg_act} and the counter reporting time so that the measurement period and the counter averaging period are synchronized. For example, if T_{avg_act} is 360 s and the counter reporting time is 900 s, the measurement time should be at least 900 s such that the power is constant during the observation time. The measured power is recorded during this period.

The BS power measured by the power meter is averaged over the actual averaging period and compared with the actual power reported by the counter and with the configured maximum power taking into account the technology duty-cycle factor F_{TDC}. Since the power is transmitted continuously at the same level, the average power corresponds to the configured maximum downlink power or, in case of TDD, to the configured maximum downlink power multiplied by F_{TDC}, see Clause B.9. Table C.1 provides examples of relative difference between the measured power and power counter value for systems that allow direct power level measurements for BS in both TDD mode and FDD mode.

Table C.1 – Relative difference between the measured averaged transmitted power and actual power counter value for systems that allow direct power level measurements

		a	b	c = 10 × log(b/a)	
Rated maximum power P_{max} (W)	F_{TDC}	Measured averaged transmitted power (W)	Actual power counter value (W)	Relative difference (dB)	Comment
100	0,75	72	75	0,18	TDD example
100	1	95	100	0,22	FDD example
NOTE 1 Column headings a, b and c are for reference and the numerical values are examples. NOTE 2 Both TDD and FDD are shown in this table for completeness but only one applies for each test. When FDD is used, F_{TDC} = 1.					

C.3.1.3 Step 2 – Counter validation for multiple configured maximum power values – power linearity

The total radio transmitted power is a function of the configured radio power and the buffer occupation. For the purposes of assessing power linearity, Step 1 is repeated for at least 5 levels of configured power with a full buffer as shown in Table C.2.

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Table C.2 – Correlation between the configured maximum power level and the level reported by actual power counters for BS that allow direct power level measurements

	a	b	c = 10 × log(b/a)
Configured maximum power (W)	Measured averaged transmitted power (W)	Actual power counter value (W)	Relative difference (dB)
10 (= 0,1 × P_{max})	6,9	7,5	0,36
30 (= 0,3 × P_{max})	21,0	22,5	0,30
50 (= 0,5 × P_{max})	35,4	37,5	0,25
70 (= 0,7 × P_{max})	50,1	52,5	0,21
90 (= 0,9 × P_{max})	64,8	67,5	0,18
NOTE Column headings a, b and c are for reference and the numerical values are examples for the case of P_{max} = 100 W and F_{TDC} = 0,75.			

C.3.1.4 Step 3 – Counter validation for multiple load levels – time linearity

Step 1 is repeated for at least three shorter power transmission intervals within the actual averaging time period (e.g. transmission for 180 s in each averaging interval of 360 s) as shown in Table C.3.

Table C.3 – Correlation between the configured time-averaged load levels and the actual power counter value for systems that allow direct power level measurements

		a	b	c = 10 × log(b/a)
Fraction of Tx time with respect to the actual averaging time (%)	Configured time-averaged power (W)	Measured averaged transmitted power (W)	Actual power counter value (W)	Relative difference (dB)
10	7,5	7,2	7,5	0,18
30	22,5	21,7	22,5	0,16
50	37,5	35,7	37,5	0,21
70	52,5	50,1	52,5	0,20
90	67,5	64,8	67,5	0,18
NOTE Column headings a, b and c are for reference and the numerical values are examples for the case of P_{max} = 100 W and F_{TDC} = 0,75.				

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C.3.1.5 Step 4 – Conclusion of the counter validation

The relative difference between the counter value and the measured maximum transmitted power (Step 1) should be within the tolerance of the rated maximum power of the BS as specified in the applicable radio compliance standards (for example 3GPP 38.141-1 [42] and EN 301908-23 [47] for NR).

Similarly, the relative difference between the counter value and the measured time-averaged power for all intermediate levels of configured power (Step 2) and load (Step 3) should be within the same tolerance.

C.3.2 Validation of power or EIRP monitoring counter in OTA mode – test procedure

C.3.2.1 General

The test setup described in B.10.3 can be used. The BS is set to generate the configured maximum power, continuously, using full buffer load, by features that can be internal to the BS or external (e.g. using UEs). Furthermore, the actual power counter is set to the selected actual averaging time (for example 360 s) and then activated. The recommended procedure consists of the steps described in C.3.2.2 to C.3.2.5.

C.3.2.2 Step 1 – Counter validation at rated maximum power and determination of the reference power

The BS is activated at the rated maximum power using full buffer load, continuously, for a period larger than T_{avg_act} and the counter reporting time (e.g. if T_{avg_act} is 360 s and the counter reporting time is 900 s, the measurement time is at least 900 s). A scan is performed over the entire sphere or the angular region covered by the measurement system. The reference azimuth position φ_{ref} and elevation position θ_{ref}, where the maximum of the power density has been found during the scan is recorded. The value of the power density S_{ref} measured in the reference position is recorded. The power radiated by the BS, obtained as the integration of the measured power density over the sphere, is referenced as the radiated power P_{ref}. The value of $EIRP_{ref}$ is derived from S_{ref} using the simple spherical formula, Equation (B.1), or any applicable calculation method described in Annex B, and the measured distance between the BS antenna and the measurement probe.

Since the power is transmitted continuously at the same level, the average power level corresponds to the maximum downlink power (or, in the case of TDD, to the maximum downlink power multiplied by the F_{TDC} factor, see Clause B.9). Examples are provided in Table C.4.

Calibration of the measurement chain should be performed.

Table C.4 – Relative difference between the configured maximum power, measured averaged transmitted power, and actual power counters for systems that do not support direct power level measurements

					a	b	c = 10 × log(b/a)	Comment
Configured maximum power (W)	**Reference azimuth** (°)	**Reference elevation** (°)		**Reference power density** (W m^{-2})	**Measured averaged transmitted power** (W)	**Actual power counter value** (W)	**Relative difference** (dB)	
P_{max}	φ_{ref}	θ_{ref}		S_{ref}	P_{ref}			
100	45	92		5,7	72	74	0,12	TDD Example; F_{TDC} = 0,75
100	45	92		7,6	96	98,7	0,12	FDD Example; F_{TDC} = 1
NOTE Column headings a, b and c are for reference and the numerical values are examples for the case of P_{max} = 100 W, 20 dBi antenna and 10 m distance.								

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C.3.2.3 Step 2 – Counter validation for multiple configured maximum power values – power or EIRP linearity

The antenna is placed in the reference position φ_{ref} and θ_{ref} where the maximum power density S_{ref} was measured in Step 1.

The antenna radiated power is a function of the configured maximum power, the buffer occupation and the antenna gain. For the purposes of measuring power linearity, Step 1 is repeated for at least five levels of configured maximum power with a full buffer as shown in Table C.5. The measured power density $S_{\%}$ at the reference point is recorded for each configuration; $S_{\%}$ is the power density measured for the configured power, that is a percentage of the maximum configurable power, see Table C.5. The same process applies to evaluate the EIRP.

The radiated power $P_{\%}$ is determined by Equation (C.1).

$$P_{\%} = P_{ref} \cdot \frac{S_{\%}}{S_{ref}} \tag{C.1}$$

where

P_{ref} is the reference power determined in Step 1;

S_{ref} is the reference power density determined in Step 1;

$S_{\%}$ is the measured power density.

NOTE It is assumed the radiation pattern does not change as the power changes.

Table C.5 – Correlation between the configured power level and the level reported by power counters for BS that do not support direct power level measurements

		a	b	c = 10 × log(b/a)	
Configured Power (W)	**Measured Power Density** ($W\ m^{-2}$)	**Measured averaged transmitted power** (W)	**Actual power counter value** (W)	**Relative difference** (dB)	**Notes**
	$S_{\%}$	$P_{\%}$			
10 (= 0,1 × P_{max})	0,56	7,08	6,84	−0,15	TDD example F_{TDC} = 0,75
30 (= 0,3 × P_{max})	1,72	21,74	21,68	−0,01	TDD example F_{TDC} = 0,75
50 (= 0,5 × P_{max})	2,84	35,81	35,81	0,00	TDD example F_{TDC} = 0,75
70 (= 0,7 × P_{max})	4,01	50,68	51,85	0,10	TDD example F_{TDC} = 0,75
90 (= 0,9 × P_{max})	5,12	64,68	66,42	0,12	TDD example F_{TDC} = 0,75
10 (= 0,1 × P_{max})	0,75	9,44	9,12	−0,15	FDD example F_{TDC} = 1,0
30 (= 0,3 × P_{max})	2,29	28,98	28,91	−0,01	FDD example F_{TDC} = 1,0

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		a	b	c = 10 × log(b/a)	
Configured Power (W)	**Measured Power Density** ($W\ m^{-2}$)	**Measured averaged transmitted power** (W)	**Actual power counter value** (W)	**Relative difference** (dB)	**Notes**
	$S_{\%}$	$P_{\%}$			
50 (= 0,5 × P_{max})	3,78	47,75	47,74	0,00	FDD example F_{TDC} = 1,0
70 (= 0,7 × P_{max})	5,35	67,58	69,13	0,10	FDD example F_{TDC} = 1,0
90 (= 0,9 × P_{max})	6,83	86,24	88,56	0,12	FDD example F_{TDC} = 1,0
NOTE Column headings a, b and c are for reference and the numerical values are examples for the case of configured maximum power P_{max} = 100 W.					

C.3.2.4 Step 3 – Counter validation for multiple load levels – time linearity

The antenna is placed in the reference position φ_{ref} and θ_{ref} where the maximum power density S_{ref} was measured in Step 1.

The antenna is configured at the rated maximum power to radiate at the reference power P_{ref} defined in Step 1, continuously, full buffer for a fraction period $T_{\%}$ of the time-averaging period T_{avg_act}. For the purposes of measuring time linearity, Step 1 is repeated for at least three fractions of the actual averaging time, as shown in Table C.6. The actual power counter is collected for a period larger than the counter reporting period (e.g. 900 s). The same process applies to evaluate the EIRP using $EIRP_{ref}$ defined in Step 1.

The radiated power $P_{\%}$ is determined by Equation (C.2).

$$P_{\%} = P_{ref} \cdot \frac{T_{\%}}{100} \tag{C.2}$$

where

P_{ref} is the reference power determined in Step 1;

$T_{\%}$ is the fraction period $T_{\%}$ of the actual averaging time T_{avg_act} when the BS is transmitting at full buffer load.

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Table C.6 – Correlation between time linearity of the configured maximum power level and the level reported by actual power counters for BS that do not support direct power level measurements

			b	c = 10 × log(b/a)	
Percentage of transmission time with respect to T_{avg_act}	**Configured maximum power** (W)	**Averaged measured power** (W)	**Actual power counter value** (W)	**Relative difference** (dB)	**Note**
10 (= 0,1 × T_{avg_act})	100	7,20	7,10	−0,12	TDD example F_{TDC} = 0,75
40 (= 0,4 × T_{avg_act})	100	28,80	30,00	0,17	TDD example F_{TDC} = 0,75
70 (= 0,7 × T_{avg_act})	100	50,40	52,00	0,13	TDD example F_{TDC} = 0,75
10 (= 0,1 × T_{avg_act})	100	9,60	9,33	−0,12	FDD example F_{TDC} = 1,0
40 (= 0,4 × T_{avg_act})	100	38,40	40,00	0,17	FDD example F_{TDC} = 1,0
70 (= 0,7 × T_{avg_act})	100	67,20	69,33	0,13	FDD example F_{TDC} = 1,0
NOTE Column headings a, b and c are for reference and the numerical values are examples for the case of maximum configurable power P_{max} = 100 W.					

C.3.2.5 Step 4 – Conclusion of the validation

The relative difference between the counter value and the measured maximum averaged transmitted power or EIRP (Step 1) should be within the tolerance of the rated maximum power or EIRP of the BS as specified in the applicable radio compliance standards (for example 3GPP 38.141-2 [43] and EN 301908-23 [47] for NR). Similarly, the relative difference between the counter value and the measured averaged transmitted power or EIRP for all intermediate levels of configured maximum power (Step 2) and load (Step 3) should be within the same tolerance.

C.3.3 Validation of control feature(s) in laboratory conditions

C.3.3.1 General

Laboratory validation of a software feature used for the control of the actual transmitted power or EIRP of a BS involves measurements of the RF EMF exposure (in case of OTA measurement of a BS with active antenna system) or power (in case of conducted mode measurement of a BS with external antennas) in a controlled laboratory environment using one or several representative samples of the BS product(s). Comparisons are made at various load levels with and without the control feature activated to verify that the feature is operating as intended and that the obtained reduction of the actual exposure corresponds to the configured actual maximum threshold value.

The procedure described in C.3.3.2 is for OTA measurements. For conducted mode measurements, the RF EMF exposure measurements should be replaced by power measurements at the antenna port using the methodology described in C.3.1. The power density baseline and the maximum time-averaged power density levels should be replaced by the corresponding measured conducted power levels.

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C.3.3.2 OTA test procedure

C.3.3.2.1 General

The test setup described in B.10.4 can be used. The BS selected for the validation test should be configured with the actual power or EIRP control feature. Control features are designed to limit the actual power or EIRP below the configured actual maximum threshold, typically expressed as a percentage of the configured maximum power or EIRP, for any traffic pattern. Figure C.1 shows an example of a test setup with a 5G BS, a UE and a broadband EMF probe used for an actual power control feature validation in a shielded laboratory environment.

The most conservative test case is when the generated traffic requires the BS to operate continuously at maximum capacity (referred to as "full buffer") leading to constant transmission at the configured maximum power when the feature is not activated. A validation test should always include this test case but can also encompass more realistic traffic variations or patterns with rapid variations (e.g. on and off behaviour) to verify that the feature controls the actual power or EIRP as intended.

If the feature allows the setting of different actual averaging times and power or EIRP thresholds, the validation can also include tests to verify the feature for different scenarios of these settings.

For the case where the BS applies beam steering, and the feature supports power control per beam or angular segment, tests should be performed for a number of directions within the beam steering range. Depending on the applicable requirements, variation of the configured maximum power and the bandwidth can also be included within these test scenarios.

A recommended laboratory validation procedure consists of the steps described in C.3.3.2.2 to C.3.3.2.5.

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Figure C.1 – Example of a laboratory test setup for validation of an actual power control feature intended for use with a 5G BS

C.3.3.2.2 Step 1 – Baseline assessment without the control feature activated

Without the control feature activated, measure and store the instantaneous and the actual EMF levels in terms of power density (RMS) or electric field strength (RMS) with the BS transmitting at the rated maximum power or at a lower configured maximum power. The measurement should be made over a period larger than the actual averaging time to obtain baseline values such as $S_{\text{baseline_inst}}$, $S_{\text{baseline_sample}}$ and $S_{\text{baseline_avg}}$, where

$S_{baseline_inst}$ is the maximum value of the power density when the transmitter is ON (i.e. corresponding to P_{TXM}) for example using a spectrum analyser;

$S_{baseline_sample}$ is the maximum value of the power density corresponding to ($P_{TXM} \cdot F_{TDC}$), for example measurement using 1 s sampling on a frequency selective equipment;

$S_{baseline_avg}$ is the actual power density using T_{avg_act}.

NOTE Equivalent notation can be used for E-field strength: $E_{baseline_inst}$, $E_{baseline_sample}$ and $E_{baseline_avg}$.

Baseline measurements can also be performed at intermediate load levels using the same protocol as for counter validation, see Clause C.3.

C.3.3.2.3 Step 2 – Power or EIRP control feature activation

Activate the power or EIRP control feature with the same actual averaging time as in Step 1, configure a power reduction factor F_{PR} and set the BS transmission to the same value as Step 1.

C.3.3.2.4 Step 3 – Validation with power or EIRP control feature activated

Measure and record the instantaneous and the time-averaged power density (RMS) or electric field strength (RMS) over a period that is at least three times the actual averaging time to verify that the performance is stable. Identify the maximum actual power density S_{max} or electric field strength E_{max} over the total measurement period. This measurement can be repeated for intermediate load levels used in Step 1 in order to compare to the baseline measurement and counters obtained in Step 1 and to check that the actual power or EIRP controlled values remain below the configured actual maximum threshold.

C.3.3.2.5 Step 4 – Control feature validation at additional configurations (power reduction factors, actual averaging times and traffic patterns)

If the laboratory validation includes variations of the power reduction factor (F_{PR}), the actual averaging time, the configured maximum power level and/or bandwidth, Steps 1 to 3, see C.3.3.2.2, C.3.3.2.3 and C.3.3.2.4, should be repeated for each different maximum power or bandwidth configuration.

For validations of features that support power or EIRP control per beam or per angular segments, Step 1 to Step 3, see C.3.3.2.2, C.3.3.2.3 and C.3.3.2.4, should be repeated for multiple representative directions. Once the counters have been validated, the control feature validation can be done using counters only or using directional, or several RF EMF measurement equipment or a combination of both.

C.3.3.3 Validation of proper operation

The power or EIRP control feature operates as intended if at least one of the following criteria a), b) or c), specified in Equation (C.3), Equation (C.4), Equation (C.5), Equation (C.6), Equation (C.7), and Equation (C.8) and depending on the equipment or method used, is satisfied, i.e. for any configured power and load level.

In case the EUT supports mMIMO or beam steering, $P_{counter}$ criteria specified in Equation (C.7) can overestimate the EIRP.

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a) $P_{\text{measured}} \leq P_{\text{baseline_inst}} \cdot F_{\text{TDC}} \cdot F_{\text{PR}}$ (C.3)

or $P_{\text{measured}} \leq P_{\text{baseline_sample}} \cdot F_{\text{PR}}$ (C.4)
(depending on the measurement equipment used);

b) $S_{\text{measured}} \leq S_{\text{baseline_inst}} \cdot F_{\text{TDC}} \cdot F_{\text{PR}}$ (C.5)

or $S_{\text{measured}} \leq S_{\text{baseline_sample}} \cdot F_{\text{PR}}$ (C.6)
(depending on the measurement equipment used);

c) $P_{\text{counter}} \leq P_{\text{TXM}} \cdot F_{\text{TDC}} \cdot F_{\text{PR}}$ (C.7)

or $\text{EIRP}_{\text{counter}} \leq P_{\text{TXM}} \cdot G_{\text{MLB}} \cdot F_{\text{TDC}} \cdot F_{\text{PR}}$ (C.8)

C.3.4 Validation of control features using in-situ measurements

C.3.4.1 General

The test setup described in B.10.5 can be used. A BS supporting the use of the actual power or EIRP control feature should be selected for the tests. The feature should be configured with an actual averaging time $T_{\text{avg_act}}$ compatible with the applicable exposure limit averaging time T_{avg} (e.g. 360 s). The feature should also be configured with one the power reduction factor (F_{PR}) or multiple values of F_{PR} in case of multiple cell segments. If the feature includes actual power or EIRP counter monitoring, this should preferably be activated.

Figure C.2 shows an example of a test setup with a UE and an EMF probe used for in-situ validation of an actual power control feature used with a 5G BS.

In-situ validation of an actual power or EIRP control feature involves measurements of the RF EMF exposure to verify that the reduction of the actual exposure corresponds to the applied power reduction factor. As such, measurements should be done for the following conditions:

a) at one or several test points within the BS cell sector; and

b) with and without the feature activated.

NOTE The procedure is not applicable for BS already put into operation with commercial traffic.

Optionally, the validation measurements can be performed at the border of the compliance boundary as determined using the actual maximum power or EIRP.

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Figure C.2 – Example of a test setup for validation of an actual power control feature implemented in a 5G BS

C.3.4.2 Test procedure

C.3.4.2.1 General

As for laboratory validations, an in-situ validation should always include "full buffer" traffic and possibly additional realistic traffic variations, see C.3.2.

The in-situ validation procedure should consist of the steps described in C.3.4.2.2 to C.3.4.2.6.

C.3.4.2.2 Step 1 – Instantaneous and time-averaged EMF levels at configured maximum power and intermediate levels

Without the power or EIRP control feature activated, measure and record the instantaneous and the time-averaged EMF levels in terms of power density (RMS) or electric field strength (RMS) with the BS transmitting at full power over a period that is larger than the actual averaging time to obtain a base-line value, $S_{\text{baseline_inst}}$ and $S_{\text{baseline_avg}}$ or $E_{\text{baseline_inst}}$ and $E_{\text{baseline_avg}}$, see C.3.3.2.1.

Alternatively (Step 1a), Step 1 can be used for the validation of actual EIRP or power monitoring counters by performing such power density (RMS) or electric field strength (RMS) measurements at intermediate time-averaged load levels activated on the BS, e.g. 10 %, 25 %, 50 %, 75 % and 100 %. The intermediate time-averaged load levels can be generated by using a connected UE adjusting the download duration in order to match the expected load value, see examples in Figure C.12. Traffic profiles and load levels can be generated either using a dedicated feature or using connected UE(s). The outcome of this Step 1a is $S_{\text{baseline_inst}}$, $S_{\text{baseline_sample}}$ and $S_{\text{baseline_avg}}$ or $E_{\text{baseline_inst}}$, $E_{\text{baseline_sample}}$ and $E_{\text{baseline_avg}}$ as a function of load.

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C.3.4.2.3 Step 2 – Power or EIRP control activation

Activate the power or EIRP control feature with the appropriate actual averaging time and power reduction factor or threshold and set the BS transmitted power to the maximum. In addition (Step 2a), if the BS is able to handle power or EIRP control per beam or per cell segment, the activation should be done using multiple combinations of power reduction factors (F_{PR}) defined per beam or per cell segment.

C.3.4.2.4 Step 3 – Instantaneous and time-averaged EMF levels with control activated at configured maximum power and intermediate load levels

Measure and record the instantaneous and the time-averaged power density (RMS) or electric field strength (RMS) over a period that is at least three times the actual averaging time in order to verify that the performance is stable. If counter data is being recorded, measurements should be taken over a time period that includes at least one full report output period of the counter (e.g. 15 min) and which starts after a time larger than T_{avg_count} such that power or EIRP samples stored before the activation of control are not included. Identify the maximum actual power density S_{max} or electric field strength E_{max} over the total measurement period.

The intermediate time-averaged load levels can be generated by using a connected UE adjusting the download duration in order to match the expected load value, see examples in C.5.3.

C.3.4.2.5 Step 4 – Instantaneous and time-averaged EMF levels with power control activated with considerations for power threshold, actual averaging times and traffic patterns

Repeat steps 2 and 3 for additional relevant power reduction factor (F_{PR}) value(s), and traffic profiles.

C.3.4.2.6 Step 5 – Validation of features that support power or EIRP control per beam or per cell segment

For validation of features that support power or EIRP control per beam or per angular segment, Steps 1 to 4 should be repeated for each selected direction simultaneously using a combination of power reduction factors in each beam or cell segment. The validation can be performed using at least one EMF measurement equipment for one beam or cell segment. Validation of the control feature on the other configured beams or cell segments can be done using counters, see examples in C.5.3.

C.3.4.3 Validation of proper operation

The validation conditions described in C.3.3.3 for laboratory validations apply also for in-situ validations.

In the case that actual power or EIRP data have been recorded using counters, an additional condition is that no counter value should exceed the set actual maximum threshold(s) level(s).

C.4 Validation test report

The results of the selected validation method(s) carried out, all information necessary for performing repeatable validation(s) and its interpretation should be reported accordingly. All the requirements of Clause 10 apply and should be provided in the validation test report, when being used as a stand-alone report.

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The validation test report of power or EIRP monitoring counters or control feature(s) should, at minimum, include the following items:

a) a description of the test setup, including photos as well connection diagrams;

b) the test sequence(s) used to test the power or EIRP monitoring counters or control feature(s), including the total duration of the test and actual averaging time (e.g. 6 min);

c) for the validation of actual power or EIRP monitoring counters in laboratory conditions in conducted mode, the results presented in the same format as Table C.1 to Table C.3;

d) for the validation of actual power or EIRP monitoring counters in laboratory conditions in OTA mode, the results presented in the same format as Table C.4 to Table C.6;

e) for the validation of control feature(s) using either in-situ measurements or laboratory conditions, plots of test sequence(s) showing the feature limits the actual power or EIRP as intended;

f) a clear statement on the conclusion of the monitoring counters and/or control features(s) validation.

C.5 Case studies

C.5.1 Case study A – In-situ validation

C.5.1.1 Overview

This in-situ validation was performed to confirm the performance of a 5G new radio (NR) BS power control feature that can be used by a network operator such that the actual transmitted power does not exceed a configured threshold P_{th} value. The value is usually chosen to achieve compliance with actual EIRP or EMF limits. The feature is integrated into BS software and controls the actual transmitted power by constantly monitoring and regulating the flow of physical resource blocks (PRB) to the radio transmitter. The feature provides a dedicated 5G counter to monitor the actual transmitted power.

The power control feature's performance was validated by comparing a series of EMF measurements under different P_{th} settings with corresponding 5G counter data. The BS was operating at 3,585 GHz (80 MHz channel width), configured for TDD mode and operating with a massive MIMO advanced antenna.

C.5.1.2 Pre-test setup and preparation

a) Test location(s) requirements: obstruction free, open area, line of sight to the BS antenna.

b) EMF measurement equipment included:

   1) spectrum analyser/frequency selective meter with time-averaging capability;

   2) isotropic electric field probe.

c) NR BS under test:

   1) A specialized network tool developed to support NR field testing was used to fully utilize (100 %) the NR channel ("full buffer" condition). The capability adds artificial loading (PRB padding) on to the NR air interface to maintain constant 100 % utilization and does not require the use of a 5G UE to establish a downlink call/data session.

   2) Downlink TDD technology duty-cycle factor F_{TDC} was 70 %.

d) Configured transmitted power threshold P_{th} settings and 5G counter data:

   1) Two settings were used, P_{th} = 100 % and P_{th} = 25 %. At 100 %, the threshold value is set to the transmitter's rated maximum power and the power control feature does not regulate the flow of PRBs to the radio transmitter. The time-averaged output power is determined by the TDD downlink duty-cycle factor which results in a time-averaged output power of 70 % of the transmitter's rated maximum power. These periods are labelled $CTRL_{OFF}$ in the plots.

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2) At 25 %, the feature actively regulates the flow of PRBs so that the time-averaged transmitted power does not exceed 25 % of the transmitter's rated maximum power. These periods are labelled $CTRL_{ON}$ in the plots.

3) Performance of the feature is captured by a dedicated 5G counter. The counter records the 6 min time-averaged transmitted power every 0,6 s (sliding window) and stores the values in contiguous blocks of 15 min (there are 1 500 samples per 15 min period). It provides statistical information about the 6 min time-averaged transmitted power.

e) General testing procedure:

1) The special network tool was used to initiate the flow of baseband data traffic that was capable of fully utilizing (100 %) the NR channel.

2) The measurement equipment performed swept frequency EMF measurements across the NR channel. The measurements were post-processed and converted to a set of 6 min sliding time-averaged results.

3) Time-averaged EMF measurements were performed with P_{th} set to 100 % followed immediately by time-averaged EMF measurements performed with P_{th} set to 25 %.

4) 5G counter data was obtained for the period of the EMF measurements.

C.5.1.3 Test setup

The validation was performed at two locations in the vicinity of the 5G massive MIMO BS antenna. The first was a line-of-sight ground-based validation which would be the most common and practical choice in most situations.

A second set of measurements were performed close to the antenna, at the general public compliance boundary. While this is generally not a typical option to pursue, it was considered that the validation would provide valuable information that would be relevant to real life situations where exposure could approach, for example, the ICNIRP general public reference level [1], [2] (e.g. on a building roof top site). These two measurement setups are shown below in Figure C.3 and Figure C.4, respectively.

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NOTE The evaluation location is 90 m from the 5G BS, in clear line of sight and the position is approximately 14° directly below bore sight.

Figure C.3 – Ground based in-situ validation setup



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Figure C.4 – In-situ validation measurement setup near the general public compliance boundary in front of the 5G massive MIMO antenna (bore sight position)

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C.5.1.4 Results

Ground-based results are shown in Figure C.5 and results obtained near the ICNIRP general public compliance boundary [1], [2] are shown in Figure C.6.

During periods when the power control feature was set to P_{th} = 100 % and not required to regulate the flow of PRBs, the measured EMF did not exceed 0,061 % of the ICNIRP general public reference level [1], [2] for ground-based measurement and 108 % for measurements in the elevated platform near the compliance boundary. For this power control feature, the 5G counter shows that actual transmitted power did not exceed 70 % of the rated maximum transmitter power; which is the actual maximum value for a TDD technology duty-cycle factor (F_{TDC}) of 70 %, see Figure C.5. Some variation in EMF levels below 0,061 % can be seen during this period which is also reflected in the 5G counter data.

Figure C.5 plot shows the EMF level as a function of time during periods when P_{th} was set to 25 % ($CTRL_{ON}$) and when P_{th} was set to 100 % ($CTRL_{OFF}$).

The switch the actual maximum threshold from P_{th} = 100 % to 25 % caused the power control feature to immediately start to regulate the flow of PRBs to limit the actual transmitted power below the actual maximum threshold value. However, transition to the new setting requires a time interval equal to the actual averaging time of 6 min. This is evident in both Figure C.5 and Figure C.6. The 5G counter data now shows actual transmitter activity not exceeding the new threshold setting of 25 % with some variation below this value which is also reflected in EMF values.

The result in Figure C.6 shows the TER at 39 % using ICNIRP general public limits [1], [2] during the period when P_{th} was set to 25 % ($CTRL_{ON}$). The TER was 108 % when P_{th} was set to 100 % ($CTRL_{OFF}$). 5G counter data relevant to this time period are shown in Figure C.5.

The change in EMF level between periods when the power control feature was active ($CTRL_{ON}$) and inactive ($CTRL_{OFF}$) was equal to the change in power control feature settings and confirmed by 5G counter data over the same periods. A transition period equal to the 6 min actual averaging time is required for the actual EMF levels to adjust to the new power control feature threshold setting.

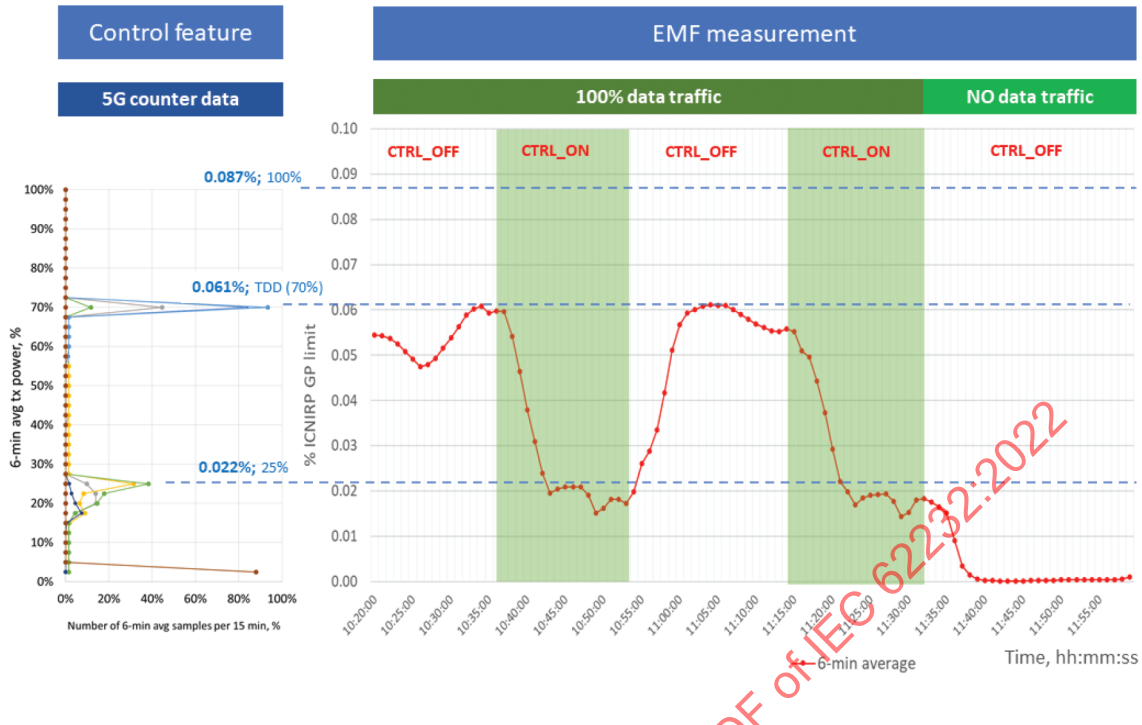


Figure C.5 – Comparison between measured time-averaged EMF and power control feature (5G counter data) for the ground-based measurements

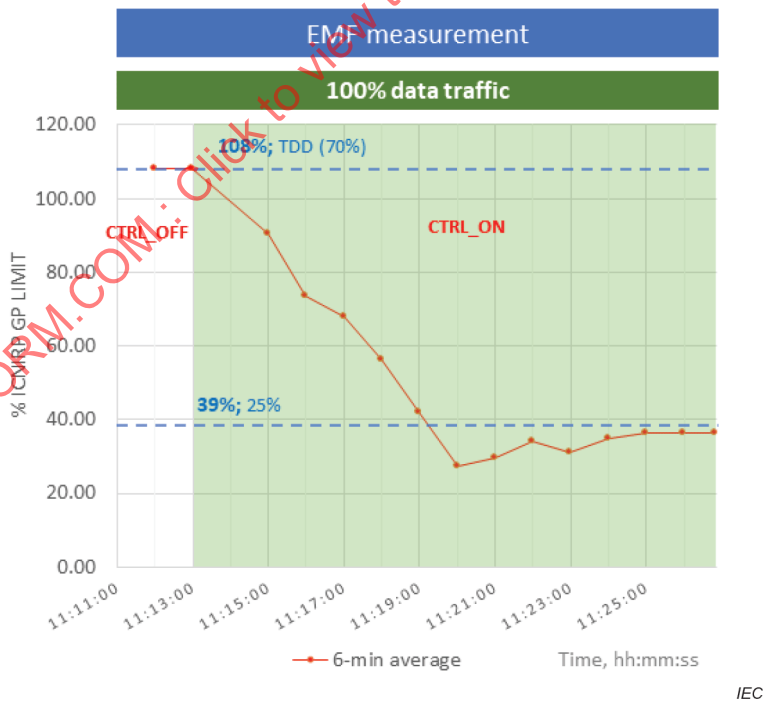


Figure C.6 – Measured exposure adaptation in time expressed as a percentage of ICNIRP limits [1], [2] for the measurements near the general public compliance boundary

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C.5.1.5 Summary

This in-situ case study for a 5G BS in a live network demonstrated that measured EMF levels were consistent with power control feature settings which in turn were reflected in network 5G counter data. This study confirmed that the feature is effective in controlling the 5G NR actual transmitted power.

C.5.2 Case study B – In-situ validation

C.5.2.1 Overview

This in-situ validation was performed with a methodology focused on the assessment of the capability of the power control feature(s) capability. The detailed results of the activity are presented in [110].

The function for controlling and monitoring the transmitted power interacts with the massive MIMO antenna downlink scheduler to dynamically reduce the momentary output power by decreasing the power of the physical downlink shared channel (PDSCH) and/or reducing the resource blocks (RBs) assigned.

The power control feature's performance is validated by comparing EMF measurements under different maximum instantaneous power transmitted by the massive MIMO antenna. The main reference quantities are the following:

P_t is the instantaneous power transmitted by the massive MIMO antenna;

P_{max} is the maximum instantaneous power that can be transmitted by the massive MIMO antenna at any time ($P_{max} \geq P_t$);

P_{avg_max} is the maximum average power that can be transmitted by the massive MIMO antenna over a time interval (e.g. 6 min);

E_{lim} is the maximum average EMF exposure allowed for the massive MIMO antenna over a time interval. E_{lim} is set in accordance with the exposure limits or applicable regulation;

P_0 is the maximum average power that results in an exposure equal to E_{lim} over a time interval;

F_{TDC} is the technology duty-cycle factor.

C.5.2.2 Pre-test setup and preparation

C.5.2.2.1 Method

The performance assessment of the power control feature is done with the following methodology.

a) Fixing of P_0

In accordance with the applicable regulation, P_0 is set in order to have an average EMF exposure over the averaging period equal to E_{lim}. In this step, the control function is disabled and $P_{avg_max} = P_0$ is forced. The value of P_{max} is determined by the following relationship: $P_{max} = P_0 + F_{TDC}$ (using decibels).

b) Increase of P_{max}

P_{max} is increased by an amount ΔP_{max} and, since P_{avg_max} is a known and fixed portion of P_{max}, when power control feature is off, P_{avg_max} is also increased by the same amount: $P_{avg_max} = P_0 + \Delta P_{max}$. Also in this step, the control function is disabled.

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c) Activation and validation of power control feature

With the increased value of P_{max}, the power control feature is activated and configured to limit the actual transmitted power to P_0.

C.5.2.2.2 EMF measurement equipment

a) Spectrum analyser/frequency selective meter with time-averaging capability to measure the channel power (ChP).

b) Isotropic electric field probe in zero span mode to measure the RF field strength.

c) Spectrum vector signal analyser (VSA) to measure the PBCH-DMRS power per RE after demodulating the 5G signal.

C.5.2.2.3 5G NR

For a proper assessment of the power control feature, it is required that P_t is equal to the maximum allowed power at all times during the validation procedure. UEs forcing UDP downlink traffic or ad hoc feature can be used to set the BS transmission to the configured maximum power.

C.5.2.3 Test setup

The proposed exposure assessment methodology is validated in a line-of-sight (LOS) environment using a commercial time-division duplexing (TDD) 3,5 GHz massive MIMO antenna system, see Figure C.7 and Figure C.8.



Figure C.7 – Overview of the measurement site

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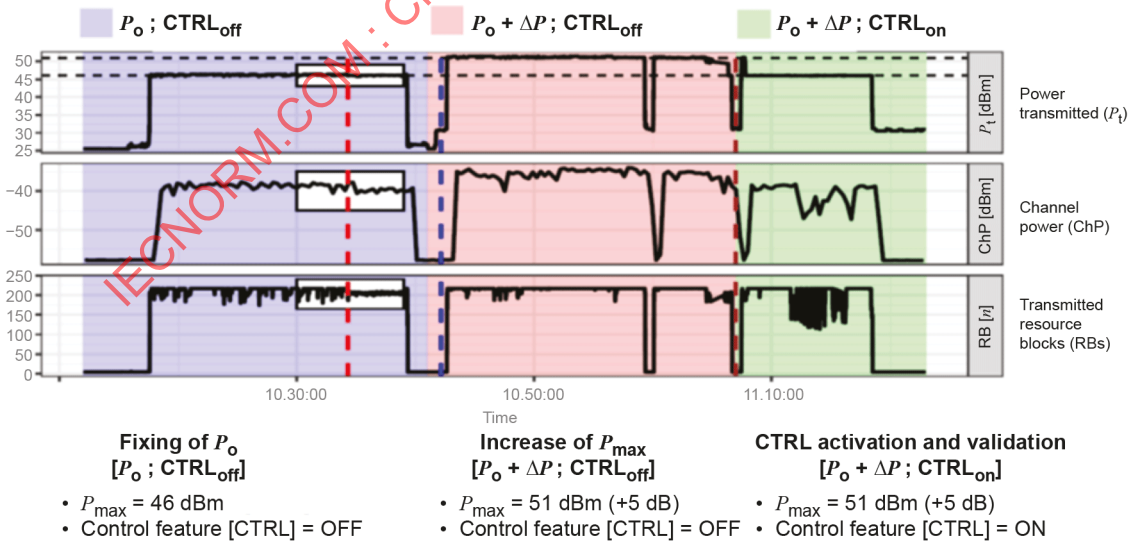
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Figure C.8 – Ground view of the validation site and measurement setup, located 60 m from the 5G BS, in the line of sight

C.5.2.4 Results

Results of the experimental validation of the methodology are shown in Figure C.9.

From Figure C.9, see [110] for a detailed results analysis, it is observed that in test b) the instantaneous power P_t increases by ΔP (see top trace) with respect to test a) and also the ChP increases (see middle trace) as expected, since there is an increased P_{max}. At the very beginning of test c), when data transmission occurs with the maximum PRBs, P_t is transmitted at the same level as test b), since the average value does not exceed P_0. Indeed, after a few seconds when $P_t = P_0 + \Delta P$, the power control feature senses that P_0 is being approached and it limits P_t to $P_t = P_0$. Moreover, from Figure C.9, thanks to the action of the power control feature, the ChP measured during test c) is equal to the ChP measured in test a).



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Figure C.9 – Power transmitted by the massive MIMO antenna (top trace), channel power (ChP) measurements (middle trace) and transmitted resource blocks (RBs) (bottom trace)

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C.5.2.5 Summary

Experimental results confirm the effectiveness of the methodology in demonstrating that the power control feature limits the actual transmitted power as expected, and that the EMF exposure limit is not exceeded.

C.5.3 Case study C – In-situ validation

C.5.3.1 Overview

The proposed method combines OTA validation of monitoring counters and control features. The following principles have been considered:

a) generate DL traffic profiles with configurable load levels using network performance tool (for example, iPerf [7] utilizing a UDP downlink transfer) scripts on test UE(s);

b) compare S measured with S derived from counters;

c) compare S with thresholds using measurements or counters or both;

d) perform measurements around local maximum to verify the value is not exceeded in other areas;

e) perform tests with multiple configurations representative of the implementation of the monitoring and control feature.

C.5.3.2 Pre-test setup and preparation

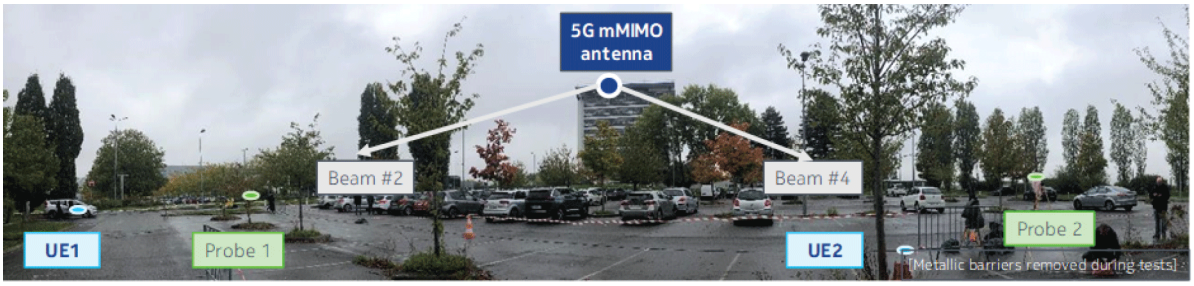
The test platform is shown in Figure C.10. It consists of a massive MIMO BS installed on a tower with one cell sector directed to a parking area where test UEs are positioned and where power density or E-field strength measurements are performed.

Performing a modelling of the test area with the BS parameters (transmitted power, beam-set configuration, tilt, azimuth of boresight) can be useful in order to identify the appropriate measurement area for each test configuration. An example of synthetic model simulation of the test area is shown in Figure C.11 where test location(s) are identified.

After the BS is configured with the beam-set, configured maximum power, RF transmission is triggered using one or multiple UEs placed in the measurement area and performing downloads in UDP downlink mode to minimize UL signal. The download can be performed using various profiles in order to adjust the average load. Examples of traffic and load profiles are shown in Figure C.12. This approach based on UEs traffic has been preferred rather than using specific BS feature generating arbitrary traffic conditions since the signal better takes into account all parameters embedded in the BS normal operations. For 100 % load (full buffer), E-field strength measurements using BS features or UE based scripts provide the same results. Load levels can be adjusted from 0 % to 100 % using 5 % steps.

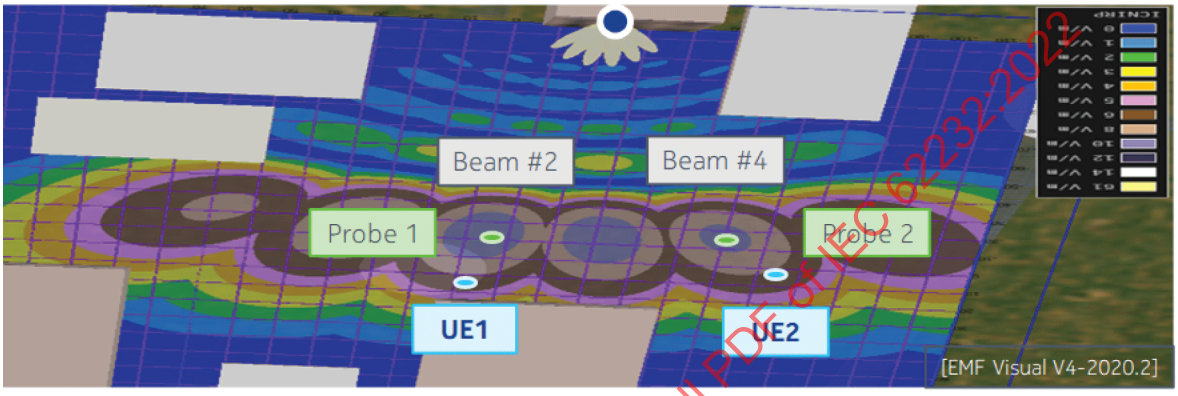
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[7] iPerf is the name of a tool supplied under BSD License (see https://iperf.fr/contact.php#authors). This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent tools can be used if they can be shown to lead to the same results.



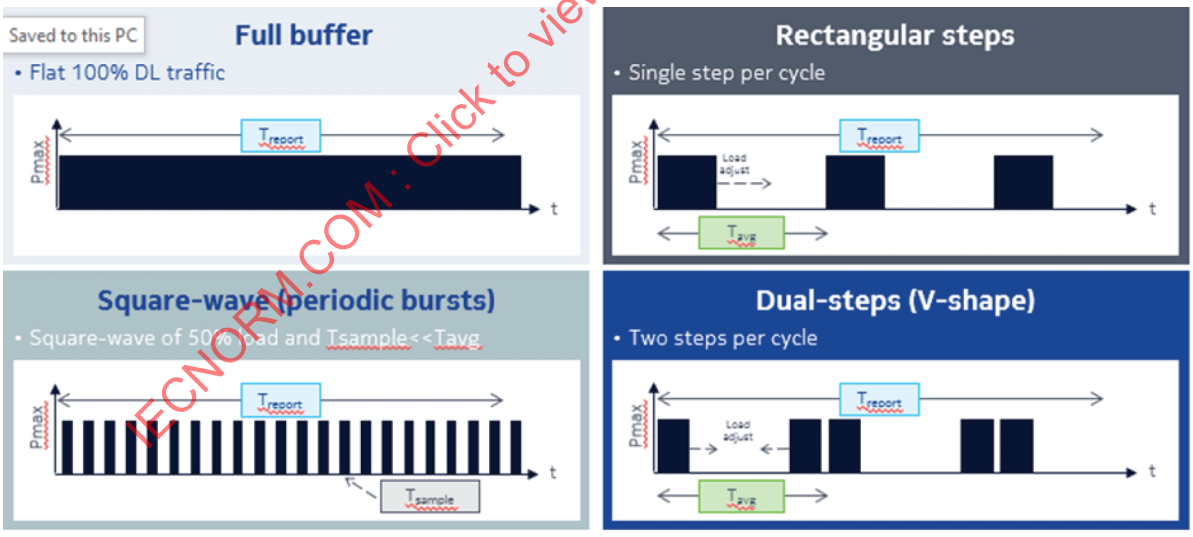
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Figure C.10 – Overview of the test platform



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Figure C.11 – Example of synthetic model simulation of the test area



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Figure C.12 – Examples of traffic load profiles

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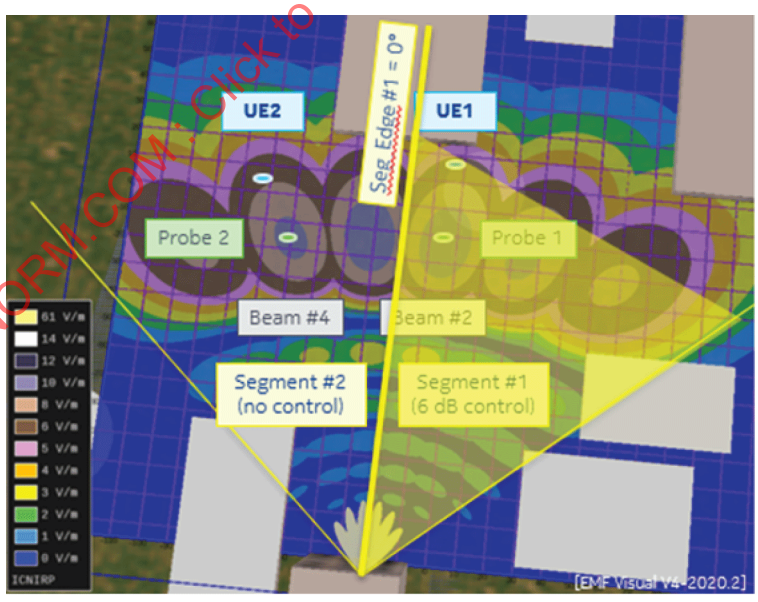
C.5.3.3 Test protocol

The test protocol is performed in three phases corresponding to the steps described in C.3.4.2.

a) Phase 1: monitoring counter validation and baseline (step 1)
   1) Position UE1 with stable reception from one beam and Probe 1 at the local maximum area.
   2) Generate DL load levels on UE(s) for example 10 %, 25 %, 50 %, 75 % and 100 %.
   3) Measure the power density S and collect counters (EIRP, power, UE load…) and traces.
   4) Compare to S_{meas} with S derived from counters S_{count}.

b) Phase 2: control feature validation on one segment (combining steps 2, 3 and 4)
   1) Same position of UE1 and Probe 1 as in phase 1/step 1.
   2) Configure the actual transmitted power or EIRP threshold (e.g. F_{PR} = −3 dB or F_{PR} = −6 dB).
   3) Generate DL load on UE1 with refined granularity around the expected threshold (for example around 25 % load for testing F_{PR} = −6 dB).
   4) Compare S_{meas} and S_{count} with the corresponding threshold.

c) Phase 3: control feature validation on two segments (step 5)
   1) Position UE2 and Probe 2 in another beam and another segment and perform baseline measurement using step 1, see Figure C.13.
   2) Configure the segment edge and thresholds for each segment (e.g. F_{PR_seg1} = −6 dB / F_{PR_seg2} = 0 dB).
   3) Generate symmetric DL load on both UEs.
   4) Compare S_{meas} and S_{count} with the corresponding thresholds.



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Figure C.13 – Example of testing in different segments in the test area

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C.5.3.4 Test results

Results from phase 1/step 1, see Figure C.14, provide the monitoring validation and baseline. Power density measurements and power density derived from actual EIRP counters using the simple spherical formula, see B.3.1, follow the expected linear trend with varying traffic load. The slope differs because of the impact of propagation conditions at the measurement evaluation location. The maximum measured baseline value at 100 % load can be below configured maximum value baseline ($P_{TXM} \cdot F_{TDC}$) derived from the operational signal frame generated by the BS during tests.

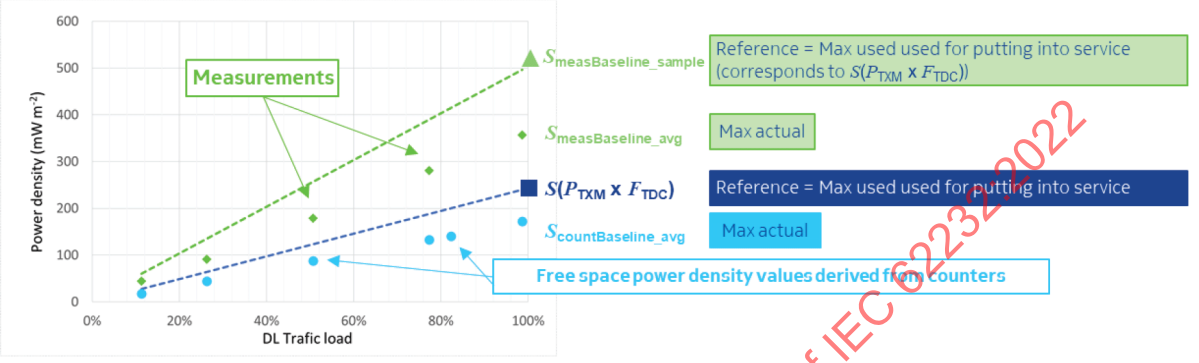


Figure C.14 – Results of the monitoring validation and baseline test in phase 1

When comparing power density measurements and power density derived from counter, it can be useful to use logarithmic unit (e.g. dBm m^{-2}) in order to better assess the ratio and the impact of external factors such as multiple reflections. Results presented in Figure C.15 show that the impact of the environment is constant and below 4 dB, see 6.3.6.

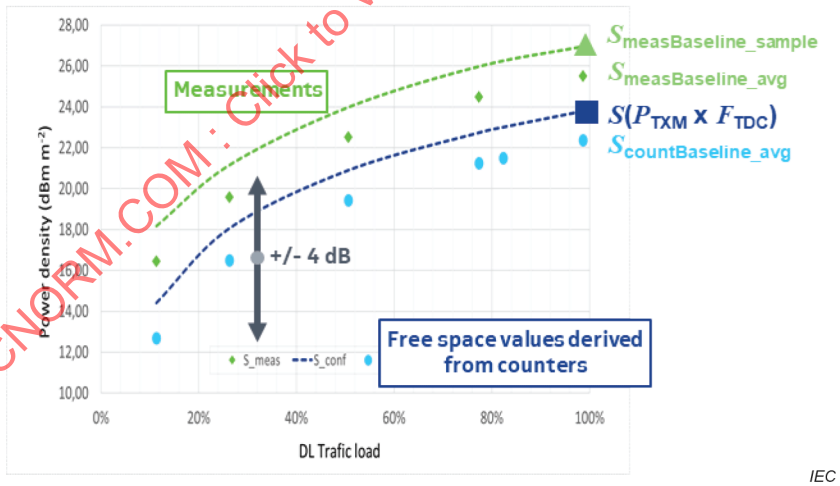


Figure C.15 – Example of power density measurements and power density derived from counters

Phase 2 results provide an assessment of the control feature on the BS cell sector for F_{PR} = −3 dB and F_{PR} = −6 dB power reduction factors. The measured power density and power density derived from counters shown in Figure C.16 consistently demonstrate that they do not exceed the configured thresholds whatever the load level generated by the UE.

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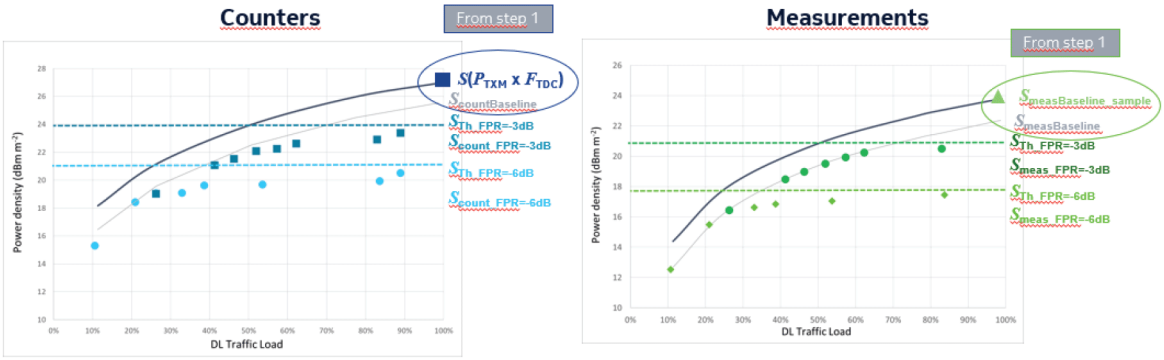


Figure C.16 – Measured power density and power density derived from counters

Phase 3 results provide an assessment of the control feature on the BS cell sector split in two segments as shown in Figure C.13. A power reduction factor of 6 dB is applied in Segment #1 while no control is applied in Segment #2 (i.e. F_{PR} = 0). Both UEs are performing downloads at the same time and share the load. Therefore, the maximum load for this type of measurement is 50 %. Both measurements and counters show that the threshold with F_{PR} = −6 dB in Segment #1 is not exceeded while there is no control observed on Segment #2, see Figure C.17.

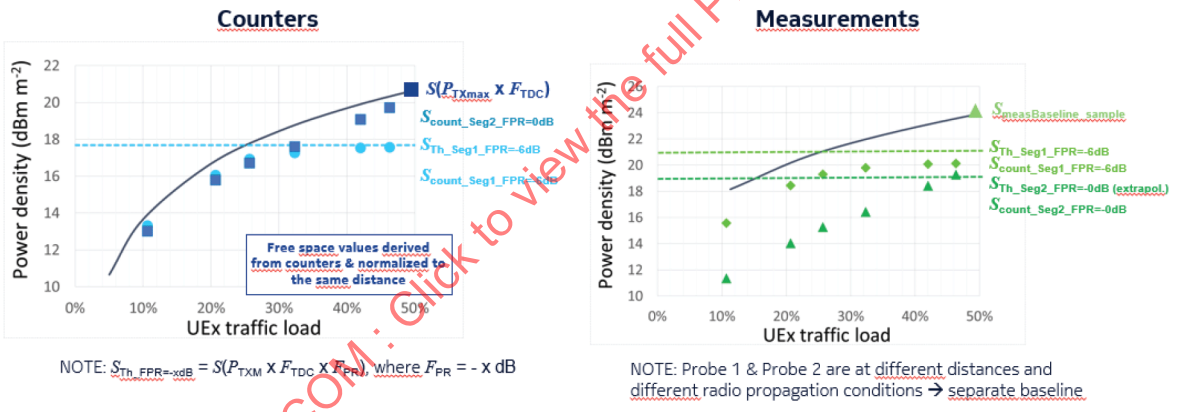


Figure C.17 – Comparisons of both counters and measurements

C.5.3.5 Summary and lessons learned

The validation tests show that the monitoring counters and control features operate as expected in 6.2.3, 8.4 and Clause B.9. When control features are implemented, the actual EIRP threshold is not exceeded per cell or cell segment. The test protocol can be reproduced on similar sites provided there is enough clearance around and access to measurement area.

Lessons learned:

a) measured values or counters should be used relative to an established baseline (i.e. relative comparison analysis);

b) direct comparison between measured level and counter level needs to consider the impact of radio propagation conditions (e.g. multiple reflexions, absorption by trees);

c) network performance tool scripts can be used to generate multiple traffic profiles, but shape and synchronization are important parameters;

d) modelling tools can support the preparation of the experiment setup, to select beams and position probes and UEs, etc.

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Annex D
(informative)

Rationale supporting simplified product installation criteria

D.1 General

The product installation classes defined in Table 2, see 6.2.5, provide simplified criteria to identify when an EUT installation is deemed to comply with ICNIRP exposure limits [1] and [2] beyond the product compliance results provided by the manufacturer in accordance with the requirements defined in 6.1.

In order to be consistent with IEC/IEEE 62209-1528 and IEC/IEEE 63195-1, the classes defined in Table 2, see 6.2.5, are based on the assumption that, when performing product installation compliance assessments as defined in this document in accordance with 6.2, ambient sources need to be considered only if the EUT has a product compliance boundary larger than 200 mm.

NOTE The scope of IEC/IEEE 62209-1528 corresponds to equipment "intended to be used at a position near the human body, in the manner described by the manufacturer, with the radiating part(s) of the device [EUT] at distances up to and including 200 mm from a human body". For products within the scope of IEC/IEEE 62209-1528, RF exposure assessment is performed without considering ambient sources.

D.2 Class E2

For EUT with an EIRP less than or equal to 2 W, compliance with the exposure limits is generally obtained at zero distance or within a few centimetres. Therefore, it is not required to investigate the contribution of ambient fields provided the EUT is installed in accordance with the manufacturer's instructions, which are based upon the product compliance results obtained in accordance with 6.1.

As an example, SAR measurements using the methodology in this document for a BS with single patch antenna element (G = 5 dBi, EIRP = 2 W, f = 2 100 MHz) are provided in Figure D.1. The uncertainty of the measurements is less than 30 % and the ER is well below 1.

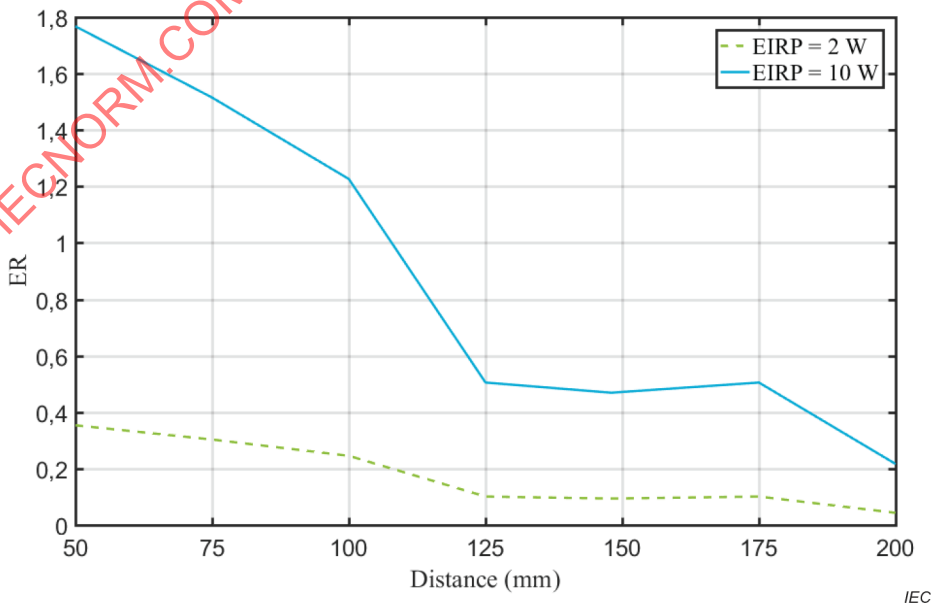


Figure D.1 – Measured ER as a function of distance for a BS (G = 5 dBi, f = 2 100 MHz) transmitting with an EIRP of 2 W (installation class E2) and 10 W (installation class E10)

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Other examples covering the frequency range from 10 GHz to 100 GHz are available in [71], which shows, based on numerical simulations of a large number of antenna arrays, that compliance with power density limits specified by [1] is within 20 cm for EIRP equal to or below 10 W.

D.3 Class E10

For EUT having an EIRP less than or equal to 10 W, product compliance distance in the main lobe is typically below 20 cm, see for example, [72] and Figure D.1. Product installation compliance is achieved by implementing a minimum installation height above the walking or standing surface accessible by the general public in order to make sure that the general public cannot enter the compliance boundary.

An example of generic assessment is provided in Figure D.2. Assuming a 2 m tall person standing beneath the antenna, the minimum installation height above the walking or standing surface accessible by the general public has been assessed using the local SAR estimation formulas for the axial direction in B.6.3.3 for a range of transmitted power values between 2 W and 5 W. In accordance with Table 3, see 7.2.3, local SAR evaluation is the preferred approach for this type of near-field exposure configuration. The following two examples correspond to equipment having an EIRP below 10 W and classify as E10:

a) EUT transmitted power of 2 W (3 dBW) with an antenna gain below 7 dBi;

b) EUT transmitted power of 5 W (7 dBW) with an antenna gain below 3 dBi.

The minimum installation height varies for different combinations of transmitted power and number of antenna elements (related to antenna gain) that are relevant for SAR evaluation. Figure D.2 shows that the minimum installation height of 2,2 m above the walking or standing surface accessible by the general public defined in Table 2, see 6.2.5, is conservative.

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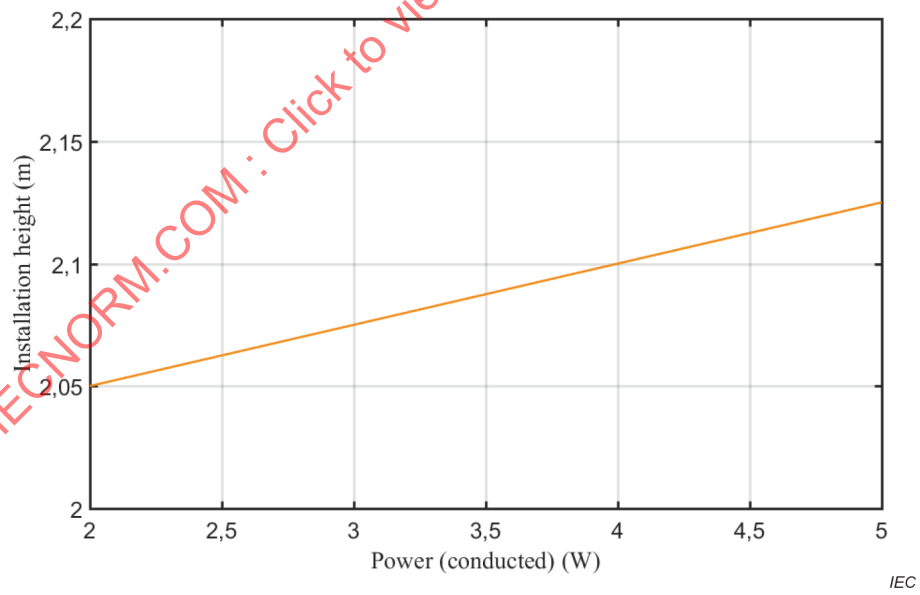


Figure D.2 – Minimum installation height as a function of transmitting power corresponding to installation class E10

Given the small compliance distance (below 20 cm), there is no requirement to investigate the contributions of ambient fields. The EUT can be installed in accordance with the manufacturer's instructions which in turn are based upon the product compliance results obtained in accordance with 6.1.

D.4 Class E100

For an EUT with an EIRP less than or equal to 100 W, as shown in Figure D.3, the product compliance distance in the main lobe is typically below 1 m for frequencies above 1 500 MHz or 2 m for frequencies between 400 MHz and 1 500 MHz, using Equation (B.1). Figure D.3 was conservatively derived based on compliance of the peak-spatial power density (i.e. without applying spatial averaging) with reference levels provided by [1] and [2], for both whole-body and localized RF exposure.

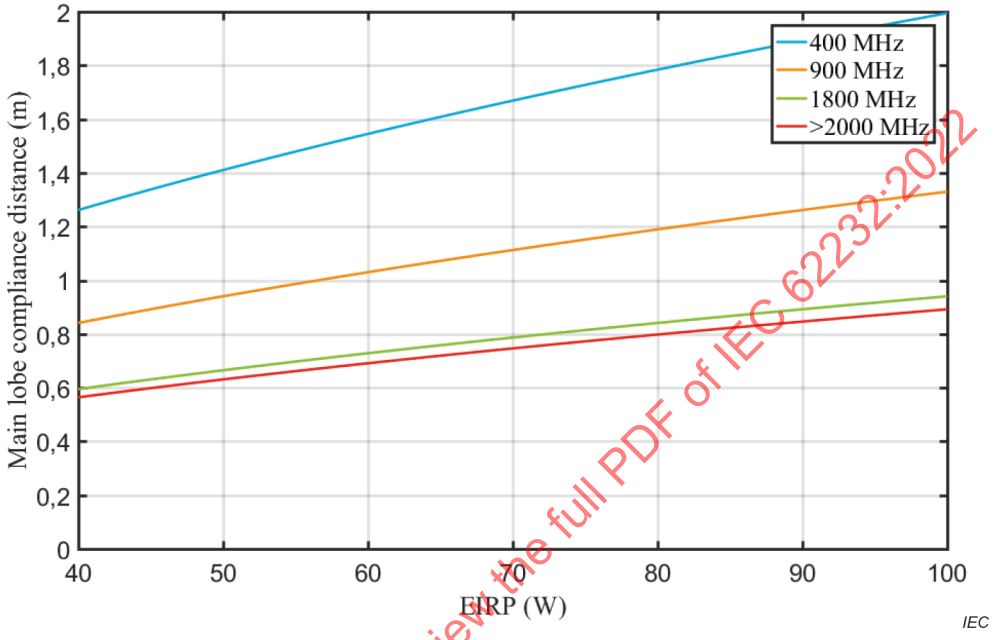


Figure D.3 – Compliance distance in the main lobe as a function of EIRP established in accordance with the far-field formula corresponding to installation class E100

An example of generic assessment is provided in Figure D.4. Assuming a 2 m tall person standing beneath the antenna, the minimum installation height has been assessed using the local SAR estimation formulas in B.6.3.3 for a range of transmitted power values between 10 W and 18 W. In accordance with Table 3, see 7.2.3, local SAR evaluation is the preferred approach for this type of near-field exposure configuration. The following two examples correspond to equipment having an EIRP below 100 W and classify as E100:

a) EUT transmitted power of 10 W (10 dBW) with an antenna gain below 10 dBi;

b) EUT transmitted power of 16 W (12 dBW) with an antenna gain below 8 dBi.

The minimum installation height varies for different combinations of conductive power and number of antenna elements (related to antenna gain) that are relevant for SAR evaluation. Figure D.4 shows that the minimum installation height of 2,5 m above the walking or standing surface accessible by the general public defined in Table 2, see 6.2.5, is conservative.

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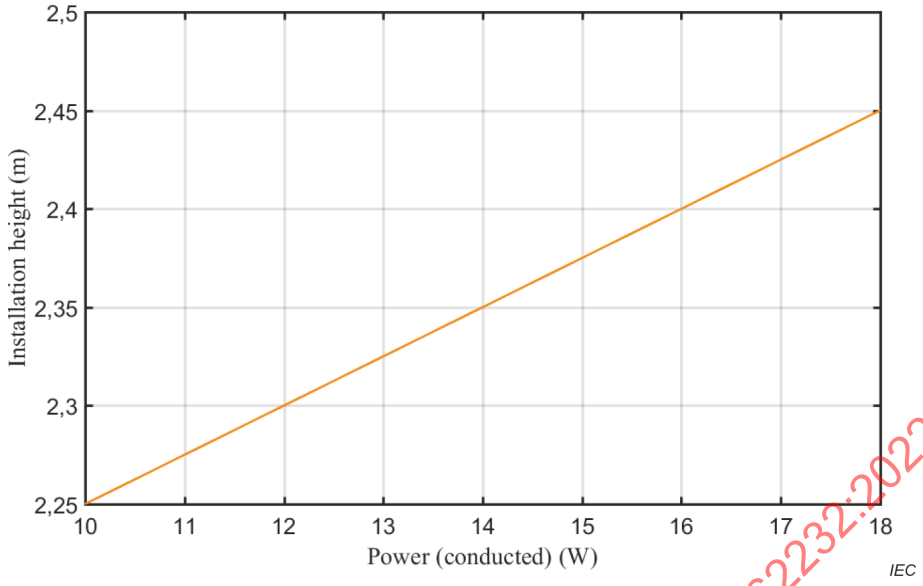
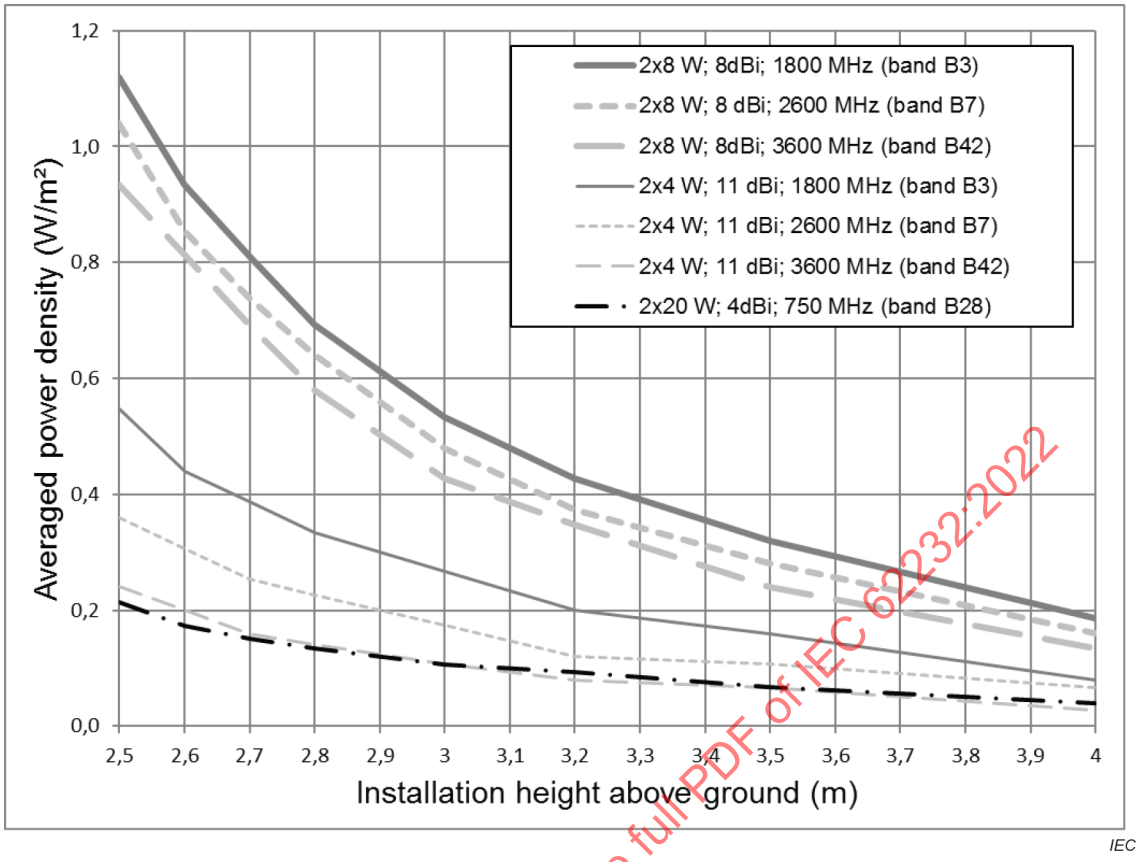


Figure D.4 – Minimum installation height as a function of transmitting power corresponding to installation class E100

Class E100 EUT can have compliance boundaries (CD_m) larger than 200 mm. Therefore, it is necessary to consider effects of possible ambient sources. Taking the approach defined in 6.2.7.4, the ER of the EUT at a distance of 5 × CD_m is below 0,05 assuming far-field propagation. Therefore, its contribution on pre-existing sources at distances larger than 5 × CD_m is not significant. For further simplification, in accordance with Figure D.4, CD_m can be assumed to be 2 m (general case) or 1 m if all EUT transmit frequencies are greater than or equal to 1 500 MHz.

Other generic assessment results are provided in Figure D.5. In this study, the spatially averaged power density at ground level is calculated using the synthetic model methods for seven typical configurations of equipment with 100 W EIRP and transmit frequencies between 700 MHz and 3 600 MHz. The installation height varies from 2,5 m to 4 m above the walking or standing surface accessible by the general public. All configurations correspond to the upper EIRP values of E100 installation class and the corresponding RF exposure levels are well below ICNIRP limits [1] and [2].

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NOTE The band Bxx (see inset) values correspond to the 3GPP bands defined in [17] and [21].

Figure D.5 – Averaged power density at ground level for various installation configurations of equipment with 100 W EIRP (installation class E100)

D.5 Class E+

For EUT having an EIRP above 100 W, there is a large range of product compliance distances in the main lobe and minimum installation heights as shown in Figure D.6 and Figure D.7, which are based on Equation (1), Equation (2) and Equation (3) specified in 6.2.5. These equations were conservatively derived based on compliance of the peak-spatial power density (i.e. without applying spatial averaging) with reference levels provided by [1] and [2], for both whole-body and localized RF exposure.

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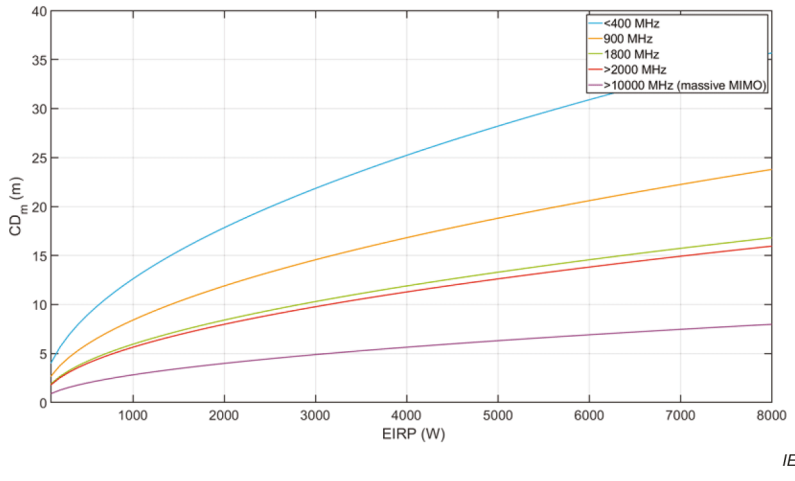


Figure D.6 – Compliance distance in the main lobe CD_m as a function of EIRP established in accordance with the far-field formula corresponding to installation class E+

The results of Figure D.7 are based on a conservative choice of antenna parameters: π/12 half-power beamwidth $\Delta\theta_{3dB}$, π/12 antenna downtilt (α, electrical and mechanical) and side lobe suppression (A_{sl}) of 0,05. h_m decreases by decreasing $\Delta\theta_{3dB}$, α and the side lobe suppression.

Class E+ EUT can have compliance boundaries (CD_m) larger than 200 mm. Therefore, it is necessary to consider effects of possible ambient sources. Taking the approach defined in 6.2.7.4, the ER of the EUT at a distance of 5 × CD_m is below 0,05 assuming far-field propagation.

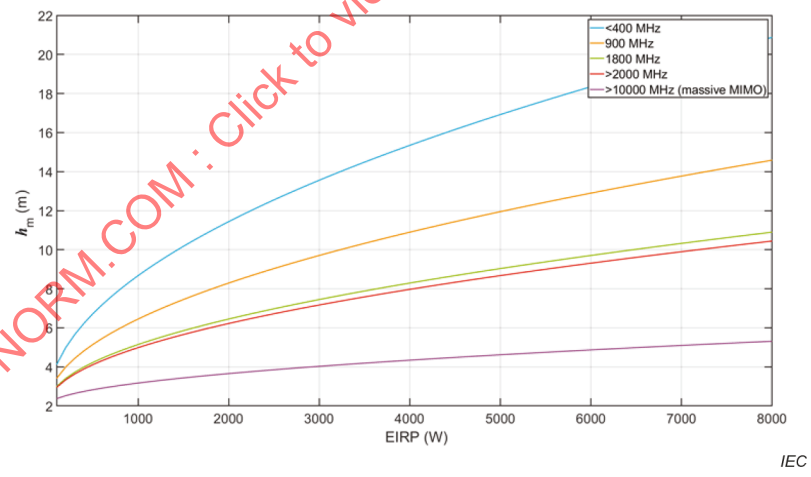
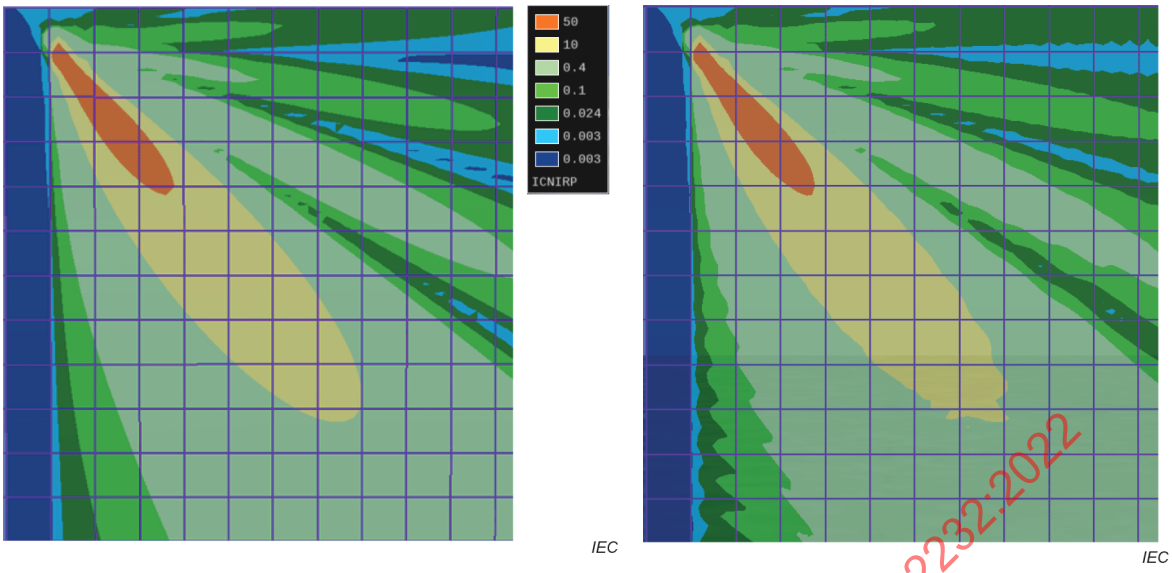


Figure D.7 – Minimum installation height h_m as a function of EIRP corresponding to installation class E+

D.6 Simplified formulas for millimetre-wave antennas using massive MIMO or beam steering

Equation (4) in 6.2.5 is derived from modelling of real BS products at various millimetre wave frequencies using the synthetic model method, see B.7.2 and details in [89]. In this paper, modelling studies were performed in free space conditions. Additional results considering metallic ground plane reflection have been produced. The power density distribution in a vertical plane yOz (see Figure B.1) is provided in Figure D.8 and Figure D.9. It demonstrates that at these frequencies, it is appropriate to neglect the impact of ground reflection.

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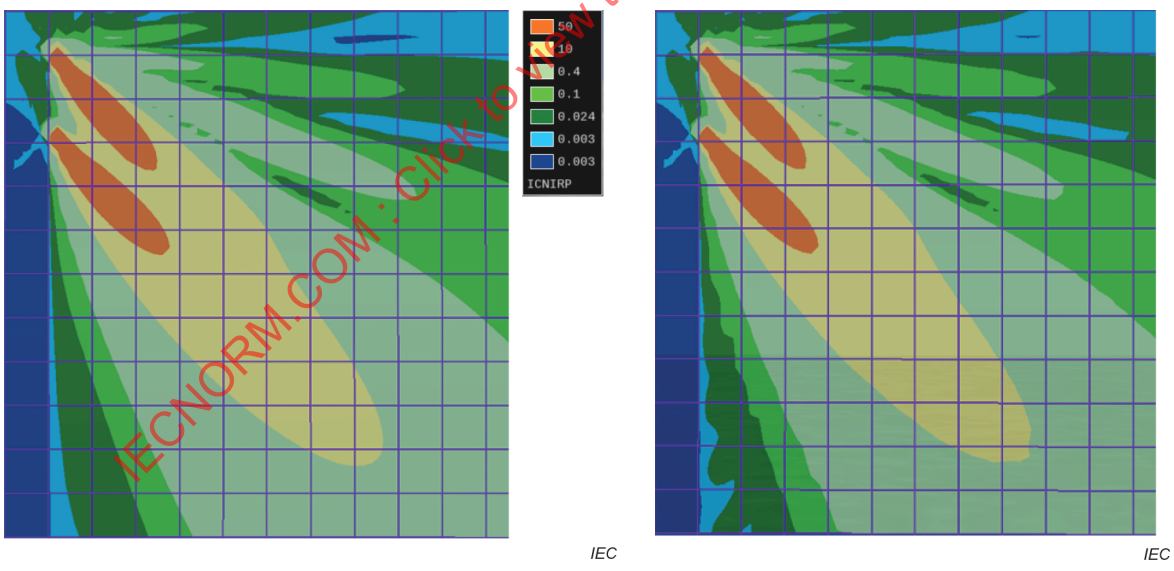


a) Free space conditions

b) Antenna installed 2,5 m above metallic ground

NOTE Modelling assumptions: 8 × 8 antenna array, 2 polarizations, frequency = 28 GHz, EIRP = 54 dBm, maximum vertical beam-steering = 45, see more in [36].

Figure D.8 – Power density distribution in watts per square metre in a vertical cut plane for an 8 × 8 antenna array at 28 GHz (grid step of 10 cm)



a) Free space conditions

b) Antenna installed 2,5 m above metallic ground

NOTE Modelling assumptions: 8 × 8 antenna array, 2 polarizations, frequency = 39 GHz, EIRP = 54 dBm, maximum vertical beam-steering = 45, see more in [36].

Figure D.9 – Power density distribution in watts per square metre in a vertical cut plane for an 8 × 8 antenna array at 39 GHz (grid step of 10 cm)

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Annex E
(informative)

Technology-specific exposure evaluation guidance

E.1 Overview to guidance on specific technologies

Annex E provides data on specific technologies and additional guidance on how to apply the evaluation methods when considering these technologies.

E.2 Summary of technology-specific information

Information provided in Table E.1 summarizes the key features of the major mobile and wireless communications technologies in operation around the world.

NOTE In some countries, it is possible that the national spectrum assignment/management agency will introduce variations of these technologies.

Table E.1 – Technology specific information

Technology	Frequency band (MHz)	Downlink freq. (base-mobile) (MHz)	Uplink freq. (mobile-base) (MHz)	Modulation type	Multiple access	Channel bandwidth (kHz)	Tx unit power (W)[a]	Downlink Tx power control range	No. of time-slots (TDMA)	Relevant technology standard references
AMPS	824 to 894	869 to 894	824 to 849	FM	FDMA	30	< ≈ 50		N/A	
C-450	450 to 465			FM	FDMA	20 / 10			N/A	
CDMA IS-95	824 to 894	869 to 894	824 to 849	QPSK	CDMA	1 250			N/A	
CDMA2000	Multiple	Multiple	Multiple	QPSK	CDMA	1 250			N/A	See 3rd Generation Partnership Project 2 (3GPP2), C.S0057
CDPD	824 to 894			FH / Packet GMSK		30				
DECT	1 880 to 1 980[b] 2 010 to 2 025 2 400 ISM	n/a (TDD)	n/a (TDD)	GFSK B·T = 0,5	TDMA	1 728	0,25 Pk 0,01 av. per channel Typical 0,01 to 0,06 for BS		24	ETSI EN 300 175-1, EN 300 175-2
GSM 900[c]	876 to 960	921 to 960	876 to 915	GMSK	FDMA / TDMA	200	0,1 to 20	≈ 30 dB (BCCH 0 dB)	8	
GSM 1800	1 710 to 1 880	1 805 to 1 880	1 710 to 1 795							
GSM / PCS1900	1 850 to 1 990	1 930 to 1 990	1 850 to 1 910							
LTE	Multiple	Multiple	Multiple	QPSK, 16QAM, 64QAM	OFDM	Multiple	Multiple		N/A	3GPP TS 36.104, TR 36.211
NR	Multiple	Multiple	Multiple	QPSK, 16QAM, 64QAM, 256 QAM	OFDM	Multiple	Multiple		N/A	3GPP TS 38.104, TS 38.211
NAMPS	824 to 894			FM	FDMA	10			N/A	
NMT-450	450 to 470			FM	FDMA	25			N/A	
NMT-900	890 to 960			FM	FDMA	12,5			N/A	

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Technology	Frequency band (MHz)	Downlink freq. (base-mobile) (MHz)	Uplink freq. (mobile-base) (MHz)	Modulation type	Multiple access	Channel band-width (kHz)	Tx unit power (W)[a]	Down-link Tx power control range	No. of time-slots (TDMA)	Relevant technology standard references
PHS	1 884 to 1 920	1 884 to 1 920	1 884 to 1 920	Multiple	TDMA	300	4		8	Association of Radio Industries and Businesses (ARIB) in Japan – RCR STD-28
TACS: JTACS	832 to 925			FM	FDMA	25			N/A	
ETACS	872 to 960	917 to 960	872 to 915							
NTACS	843 to 925					12,5				
TETRA	Below 1 000	390 to 400 420 to 430 460 to 470 851 to 867 915 to 921	380 to 390 410 to 420 450 to 460 806 to 822 870 to 876	π/4 DQPSK	TDMA	25	4			ETSI TS 100 392-15
TETRAPOL				GMSK	FDMA	10				www.tetrapol.com
UMTS (W-CDMA)	Multiple	Multiple	Multiple	QPSK	CDMA	5 000	20		N/A	3GPP TS 25.104,
USDC	824 to 894	869 to 894	824 to 849	π/4 DQPSK	TDMA	30			6	
Wi-Fi	2 400 to 2 483,5 5 150 to 5 850	n/a (TDD)	n/a (TDD)	Multiple	OFDM		0,25 typical 1 max. (national regulations can exist)			IEEE 802.11 series, IEEE 802.11b and IEEE 802.11g at 2,45 GHz, IEEE 802.11a (ETSI HyperLAN) at 5 GHz
WiMAX	Multiple	n/a (TDD, FDD)	n/a (TDD, FDD)	Multiple	OFDM	Multiple	20 (BS) 0,5 (CPE) 0,2(mob)		128, 256, 1 024, 2 048 OFDM sub-carriers	IEEE 802.16-2004, IEEE 802.16e
XGP (Next generation PHS)	2 545 to 2 625	2 545 to 2 625	2545 to 2 625	Multiple	Multiple	Multiple	10(BS) 0,2(MS)		8	Association of Radio Industries and Businesses (ARIB) in Japan – RCR STD-T95

[a] For systems not using continuous power transmission like TDMA in GSM, peak and average power can be indicated.

[b] In Europe – Frequency Band: possible 1 880 MHz to 1 980 MHz, 2 010 MHz to 2 025 MHz or 2,4 GHz ISM, typical allocation (Europe): 1 880 MHz to 1 900 MHz.

[c] Includes GSM-R, E-GSM and primary GSM bands.

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E.3 Guidance on spectrum analyser settings

E.3.1 Overview of spectrum analyser settings

Clause E.3 provides guidance on the spectrum analyser settings required to measure signals from different technologies. Accurate measurement with a spectrum analyser requires the configuration of parameters such as:

a) detection mode;

b) resolution bandwidth (RBW) and span (or f_{start} and f_{stop});

c) video bandwidth (VBW).

Annex E is not intended to be a substitute for specific equipment guidance and/or specialist training.

E.3.2 Detection algorithms

Spectrum analysers usually offer different detection modes. This is because the spectral trace is divided into $N-1$ buckets of size $\delta f = \frac{f_{\text{stop}} - f_{\text{start}}}{N-1}$ as a result of the sampling process. Equation (E.1) is assume for purposes of this discussion.

$$f_k = f_{\text{start}} + k \cdot \delta f \quad \text{with } 0 \le k \le N-1 \tag{E.1}$$

- In "sample" mode, the sample v_k corresponds to the voltage at frequency f_k.
- In "peak" mode, the sample v_k corresponds to the maximum voltage found between frequency $f_k - \delta f$ and f_k.
- In "average" mode, the sample v_k corresponds to the average voltage between frequency $f_k - \delta f$ and f_k.
- For true RMS mode, m voltage samples u_i within the interval $f_k - \delta f$ to f_k are taken. v_k is the root mean square of these u_i as described in Equation (E.2).

$$v_k = \sqrt{\frac{1}{m} \cdot \sum_{i=1}^{m} u_i^2} \tag{E.2}$$

The sweep time should be long enough to have m samples.

With the reference resistance Z_{r}, the power, p_k, is determined by Equation (E.3).

$$p_k = \frac{v_k^2}{Z_{\text{r}}} \tag{E.3}$$

In peak mode this calculation leads to a correct power p_k when measuring CW amplitude. However, it leads to a bias when measuring noise-like signals such as UMTS signals and does not allow channel power processing because samples are not equally spaced in frequency and the signal shape is not taken into account.

E.3.3 Resolution bandwidth and channel power processing

E.3.3.1 Measurement at a single frequency

For narrowband signals, the RBW parameter should be chosen in accordance with channel bandwidth and carrier spacing. An RBW higher than carrier spacing would prevent frequency selectivity analysis whereas an RBW lower than channel bandwidth would require additional processing. For GSM, the carrier spacing is equal to 200 kHz. Figure E.1 presents the frequency occupancy of a GMSK modulation with a parameter BT = 0,3. The dotted line represents the power integrated with an ideal (i.e. rectangular) filter of variable bandwidth. The solid line represents the power integrated with a real filter with variable bandwidth. The dashed line represents the power integration of an adjacent channel (spaced 200 kHz from the target channel) with a real filter.

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The real filter shape is obtained using the trace of a pure sine wave signal measured with an RBW equal to 300 kHz. Other filter bandwidths are obtained by extrapolation from this trace, assuming that the shape remains the same. The GMSK signal is given by a signal generator output measured with an RBW equal to 1 kHz and VBW equal to 10 kHz.

On the one hand, an RBW of 300 kHz would include the whole power of the target channel in the case of a perfect filter, but it would result in a loss of 0,3 dB with a real filter, with a rejection of −4,3 dB of the power of an adjacent channel. On the other hand, an RBW of 100 kHz would entail a loss of 1,8 dB. With an RBW of 200 kHz, the loss for target channel is 0,6 dB and the rejection of an adjacent channel is −7,9 dB.

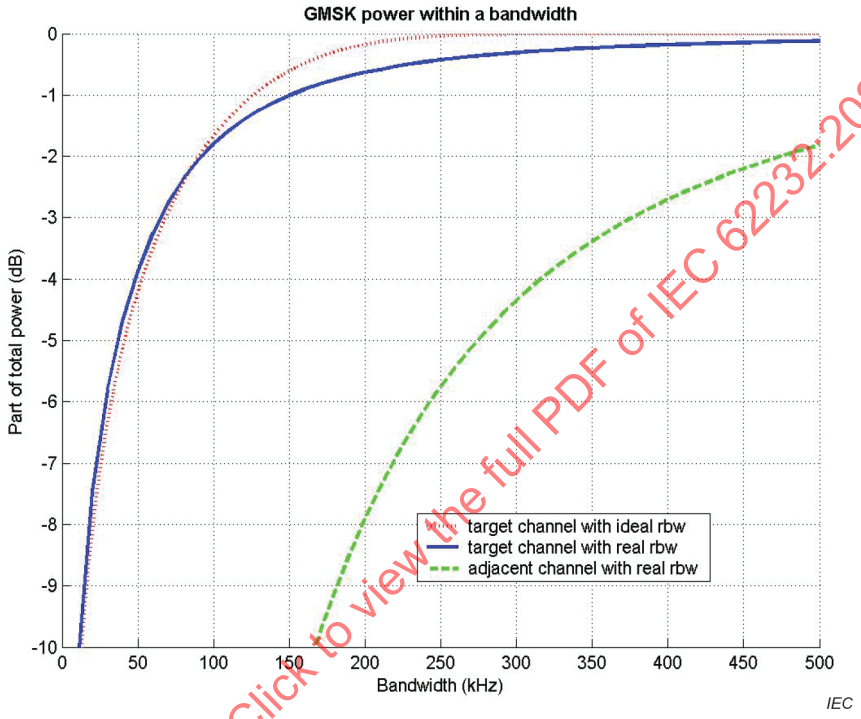


Figure E.1 – Spectral occupancy for GMSK

Figure E.2 presents the frequency occupancy of a UMTS (CDMA) signal. The real filter shape is obtained using the trace of a pure sine wave signal measured with the RBW equal to 5 MHz. Other filter bandwidths are obtained by an extrapolation from this trace, assuming that the shape remains the same. The UMTS signal is given by a signal generator output measured with the RBW equal to 1 kHz and VBW equal to 10 kHz.

An RBW of 3 MHz results in a loss of 1,7 dB, and an RBW of 5 MHz results in a loss of 0,8 dB, with a rejection of about −9,3 dB of an adjacent channel. Moreover, as the CDMA signal is a noise-like signal, VBW averaging in log scale can lead to a biased measurement. If the ratio VBW/RBW is high enough (usually 3 or 10), the averaging effect of the VBW filter does not significantly affect power detection accuracy. However, when an appropriate VBW filter is not available, it is important to perform measurements in a linear scale or to use channel power method with a lower RBW.

Finally, if the detection mode "sample" is used, it is important to choose f_{start}, f_{stop} and N so that f_k corresponds to channel carrier frequencies. In this manner, RBW filters are centred on carrier frequencies. This precaution allows the use of a corrective factor when an appropriate RBW is not available and should limit inaccuracy in measurements.

NOTE All these results depend on the shape of the RBW filter that is used.

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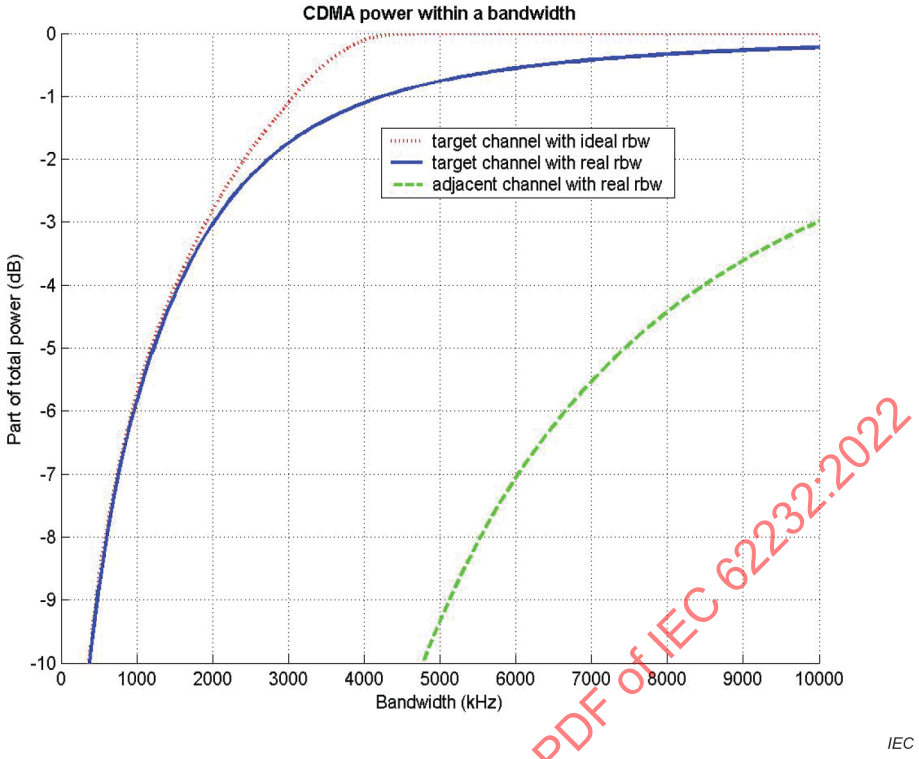


Figure E.2 – Spectral occupancy for CDMA

E.3.3.2 Measurement over a bandwidth and channel power processing

For wideband signals or for unknown signals, additional processing is required to establish the channel power. Several samples need to be summed to evaluate the power within a channel or within a whole frequency band. To reduce the effect of filter imperfections, an overlap criterion on RBW has to be verified, see the recommendations of the spectrum analyser manufacturer. Channel power over $[f_{k1}, f_{k2}]$ has to be determined in linear scale. Total power P (in dBm) is given by Equation (E.4).

$$P = 10 \cdot \log_{10}\left(\mathrm{CF} \times \frac{\delta f}{\mathrm{RBW}} \times \sum_{k_1}^{k_2} 10^{p_k/10} \right) \tag{E.4}$$

Where CF is a fitting parameter to correct RBW imperfections, see Equation (E.5).

$$\mathrm{CF} = \frac{\mathrm{RBW}}{B_n} \tag{E.5}$$

where B_n is the equivalent noise bandwidth of the filter.

Channel power process simulates the use of a sharp RBW filter of wanted bandwidth.

Finally, spectral contributions whose level is around the measuring equipment's noise level should not be considered in channel power processing. This amounts to a threshold zeroing.

NOTE Measurement equipment with a high noise level reduces the overall system sensitivity. Moreover, built-in channel power does not allow noise to be removed.

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E.3.4 Integration per service

E.3.4.1 General

The channel power measurement can be used to integrate RF field strength over a frequency band or service, e.g. the whole GSM band. In this case, spectral contributions whose level is around the equipment noise level should not be considered in channel power processing. This amounts to a threshold zeroing.

NOTE Measuring equipment with a high noise level reduces the overall system sensitivity. Moreover, built-in channel power does not allow noise to be removed.

E.3.4.2 Example of settings

Table E.2 shows the settings for a spectrum analyser with 401 points in a trace, i.e. the span is divided in 400 intervals. The purpose is to perform channel power processing to achieve an integration per service. The presented parameters should be reviewed and modified in accordance with the type of spectrum analyser used (primarily due to the number of points in a trace, the overlap criterion for channel power, etc.). For the GSM and DCS bands, the RBW filters are centred on the carrier frequencies and an extrapolation processing is also possible instead of a channel power processing. Table E.2 provides further examples.

Table E.2 – Example of spectrum analyser settings for an integration per service

Band	f_{start} (MHz)	f_{stop} (MHz)	RBW (MHz)	VBW (MHz)	Post-processing
FM	80	120	0,3	3	Channel power + denoising
DAB	174	230	0,3	3	Channel power + denoising
TV	470,2	670,2	1	3	Channel power + denoising
TV	670,2	870,2	1	3	Channel power + denoising
GSM	925	965	0,3	3	Channel power + denoising or extrapolation
DAB	1 452	1 492	0,3	3	Channel power + denoising
DCS	1 800	1 880	0,3	3	Channel power + denoising or extrapolation
DECT	1 880	1 900	0,1	1	Channel power + denoising
UMTS	2 100	2 180	0,3	3	Channel power + denoising
LTE	2 620	2 690	0,3	3	Channel power + denoising or extrapolation
NR (FR1)	3 490	3 800	1	10	Channel power + denoising or extrapolation
NR (FR2)	26 600	27 400	1	10	Channel power + denoising or extrapolation

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E.4 Stable transmitted power signals

E.4.1 TDMA/FDMA technology

TDMA mobile phone technology (e.g. GSM or TETRA) and FDMA mobile phone technology (e.g. TETRAPOL, TACS) utilize a time invariant BS radio channel that operates at constant full power and can be used as a stable reference signal.

For example, in the GSM system this stable channel power is known as the broadcast control channel (BCCH). Additional radio channels are utilized as traffic requirements demand. These signals are subject to significant amplitude variation and sometimes frequency hopping. This requires assumptions to be made to quantify their contribution to the overall RF field. Table E.3 lists constant power components for various technologies.

Table E.3 – Example constant power components for specific TDMA/FDMA technologies

Technology	Stable transmitted power signals
AMPS/TACS	Control channel
GSM	BCCH
TETRA	MCCH
TETRAPOL	MCCH

If the traffic channels each operate at a maximum power equal to the constant power component, then a conservative maximum transmitted power, P_{asmt}, see B.8, can be determined by multiplying the power of the stable transmitted power signals, P_{stable}, by the total number of radio channels (control and traffic) that feed into the antenna, N_{c}.

If P_{asmt} represents the required assessment configuration, and the RF field strength, power density or SAR of the constant power component has been evaluated, extrapolation is performed in accordance with B.8.1, and if there are no other parameters relevant, the extrapolation factor, F_{ext}, can be using Equation (E.6).

$$F_{\text{ext}} = \frac{P_{\text{asmt}}}{P_{\text{stable}}} = N_{\text{c}} \tag{E.6}$$

If the evaluated RF field strength from the constant component of the signal is E_{stable} then the extrapolated maximum RF field strength E_{max} is provided in Equation (E.7).

$$E_{\text{asmt}} = E_{\text{stable}} \cdot \sqrt{N_{\text{c}}} \tag{E.7}$$

E.4.2 WCDMA/UMTS technology

WCDMA/UMTS mobile technology uses spread spectrum technology employing a constant power control/pilot channel (embedded in the carrier) which has a fixed power relationship to the maximum allocated power. Instruments are available that enable the constant power reference channel (e.g. common pilot channel (CPICH) in UMTS/WCDMA) to be decoded and measured allowing a calculation of maximum RF field strength to be made.

If the ratio of the maximum allocated power to the power in the control channel is β and the measured RF field strength from the control channel is E_{CPICH} then the extrapolated RF field strength is specified in Equation (E.8).

$$E_{\text{asmt}} = E_{\text{CPICH}} \cdot \sqrt{F_{\text{ext}}} \tag{E.8}$$

If there are M detected and extrapolated CPICH channels, the total extrapolated field, E_{asmt} for one carrier frequency can then be expressed as the quadratic sum of all M detected and extrapolated CPICH channels as specified in Equation (E.9).

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$$E_{\text{asmt}} = \sqrt{\sum_{i=1}^{M} (E_{\text{max}}^2)_i} \quad \text{(E.9)}$$

NOTE The parameters F_{ext} and M are set by the telecommunications operator. A typical value for F_{ext} is 10 (i.e. 10 % of total power allocated to CPICH).

E.4.3 OFDM technology

Orthogonal frequency division multiplexing (OFDM) technology has been developed to enhance the capacity related to the total data throughput, see 3GPP TS 36.104 [21], 3GPP TS 36.211 [18], [111], [112], [113]. It can be implemented using frequency domain duplex (FDD) or time domain duplex (TDD). More detail is provided in Clause E.7 and Clause E.8.

E.5 WCDMA measurement and calibration using a code domain analyser

E.5.1 WCDMA measurements – General

Clause E.5 presents a method for measuring WCDMA (UMTS) signals, see 3GPP TS 25.104, and for the calibration of measurement equipment. Calibration addresses both the absolute (E_c) and the relative (E_c/I_o) level of the CPICH power. Figure E.3 shows the channel allocation for a WCDMA signal. I_o denotes the total received power over 5 MHz. The procedure focuses on both the generator and the WCDMA decoder.

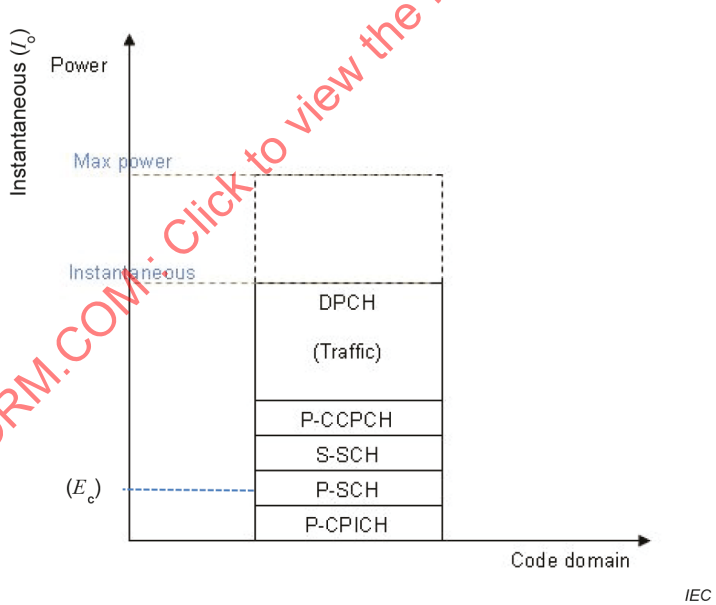


Figure E.3 – Channel allocation for a WCDMA signal

E.5.2 WCDMA decoder characteristics

A code domain analyser should be used to perform WCDMA measurement since other WCDMA BS can operate at the same frequency sharing the same bandwidth. The WCDMA decoder characteristics are listed in Table E.4.

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Table E.4 – WCDMA decoder characteristics

WCDMA scanner	
Type	UMTS scanning and decoding Detection of scrambling codes (SC)
Measuring parameters	The decoder should measure at least two of the following parameters: • I_o (total received power over 5 MHz centred on the carrier frequency in dBm) • E_c (CPICH absolute power in dBm for one scrambling code) • E_c/I_o (in dB)
Detection mode	RMS and sample
Frequency band	2 110 MHz to 2 170 MHz or as required for national frequency allocation
Number of detected SC	At least 4 per carrier frequency
Scanning mode	Automatic scanning of all scrambling codes per carrier frequency
Dynamic	≥ 66 dB for I_o (power dynamic) ≥ 20 dB for E_c/I_o(decoding dynamic)
Precision	±2 dB
Multi-path (rake fingers)	Sum of all fingers

E.5.3 Calibration

E.5.3.1 Signal types used for calibration

To detect the primary pilot channel (P-CPICH) component of a UMTS signal, at least the synchronization channels named the primary synchronization channel (P-SCH), the secondary synchronization channel (S-SCH) and the primary common control physical channel (P-CCPCH) should be present, too. Further channels can be added for signalling and traffic. The signal configurations described in Table E.5 should be used.

Table E.5 – Signal configurations

Signal name	Channel power (dB) in reference to the signal total emitted power, P_{total}				Other channels (signalling and traffic)
	P-CPICH	S-SCH	P-SCH	P-CCPCH	
CP-3.2	−3,2	−3,2	−3,2	−3,2	None
CP-0.5	−0,5	−10,5	−10,5	−10	None
CP-10	−10	−13	−13	−10	DPCH = −0,97 dB
CP-20	−20	−20	−20	−20	DPCH = −0,092 dB
NOTE 1 S-SCH and P-SCH are interleaved within the P-CCPCH. NOTE 2 All the given values are referenced to the total signal power noted P_{total}.					

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E.5.3.2 Source (generator) calibration

The configurations listed in Table E.6 should be used.

Table E.6 – WCDMA generator setting for power linearity

Signal	Total emitted power P_{total} (dBm)	Frequency (GHz)
CP-10	−20	2,14
CP-10	−40	2,14
CP-10	−80	2,14

The total received power should be measured using a precision thermal power meter or a spectrum analyser directly linked to the generator. In the case of a spectrum analyser, a channel power over 5 MHz should be used. The spectrum analyser or the power meter should be calibrated with an uncertainty of ±0,5 dB.

The total deviation between the total emitted power (P_{total}) and the total received power over 5 MHz (I_o) centred on the carrier frequency should not exceed ±1 dB in the calibration power range.

E.5.3.3 WCDMA decoder calibration

The calibration of the WCDMA decoder needs a calibrated source generator and two different approaches can be used to calibrate such a decoder:

a) use one single source for the calibration of all the WCDMA user equipment [114];

b) use two or more different generators for performing individual calibration [115].

To verify the frequency response, linearity and influence of traffic channels on the WCDMA decoder, the measurements of P-CPICH channel power are performed under the conditions given in Table E.7.

The P-CPICH power is compared to the expected target P-CPICH value, resulting in a calibration factor which should not exceed 2 dB in all the configurations.

Table E.7 – WCDMA generator setting for decoder calibration

Signal type	Frequency (GHz)	P_{total} (dBm)	P-CPICH target (dB)	Calibration type
CP-3.2	2,11	−20	−3,2	Frequency response
CP-3.2	2,17	−20	−3,2	Frequency response
CP-3.2	2,14	−10	−3,2	Linearity
CP-3.2	2,14	−30	−3,2	Linearity
CP-3.2	2,14	−40	−3,2	Linearity
CP-3.2	2,14	−50	−3,2	Linearity
CP-0.5	2,14	−20	−0,5	Traffic
CP-10	2,14	−20	−10	Traffic
CP-20	2,14	−20	−20	Traffic

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The frequency response of the reflection coefficient is measured with an SWR bridge at the input of the equipment to be calibrated under the conditions in Table E.8.

These measurements are needed to estimate the uncertainty of the measurements.

Table E.8 – WCDMA generator setting for reflection coefficient measurement

Signal type	Frequency (GHz)	P_{total} (dBm)
CP-3.2	2,11	−20
CP-3.2	2,14	−20
CP-3.2	2,17	−20

E.6 Wi-Fi measurements

E.6.1 General

The Wi-Fi®[8] signal is a spread-frequency signal emitted with random backoff. Therefore, measurements should be carried out carefully since the signal is noise-like and not permanent. Moreover, most spectrum analysers are not able to record the entire trace. Figure E.4 shows an example of Wi-Fi frames.

The evaluation of the relevant RF field strength from a Wi-Fi system implies the knowledge of the real emitted power by the EUT. In most commercial IEEE 802.11 user equipment, the access to the medium is done by a CSMA/CA (Carrier Sense Multiple Access) protocol completed by a random wait time before retrial, known as backoff time. Even if the maximum output power is constant and known and power control is not performed, the random backoff time renders it impossible for most spectrum analysers to retrieve the emitted power shape over the time period.

Wi-Fi (802.11) has advanced through several new generations (802.11 a/b/g/n/ac/ax) that are mostly based on OFDM and include MIMO and beamforming. Wi-Fi operates in the 2,4 GHz and 5 GHz bands with signal bandwidths ranging from 20 MHz to 160 MHz.

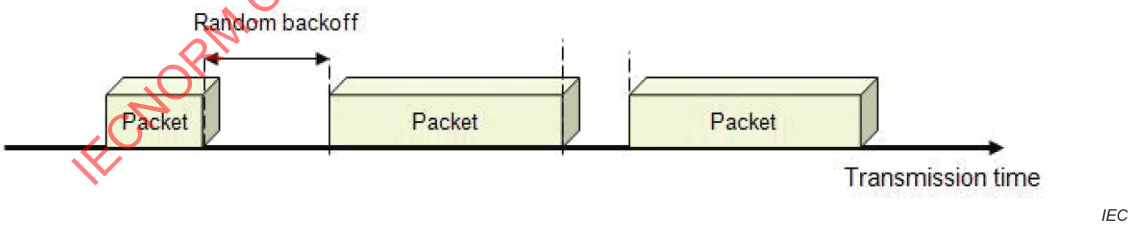


Figure E.4 – Example of Wi-Fi frames

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8 Wi-Fi® is a trademark of the Wi-Fi Alliance. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC. While officially the term does not have a specific definition, it is typically used to describe Wireless Local Area Networks such as IEEE 802.11b/g/n/ac.

E.6.2 Integration time for reproducible measurements

The random duration of the backoff time, integrated within the inter-packet delay, makes a deterministic calculation of the channel occupation impossible. Moreover, a sequence of random inter-packet delays introduces a needed minimum integration time on the random duty-cycle or channel occupation. A set of random backoff time values converge after a minimum observation time has elapsed. Figure E.5 shows how the indicated channel occupation varies with integration time.

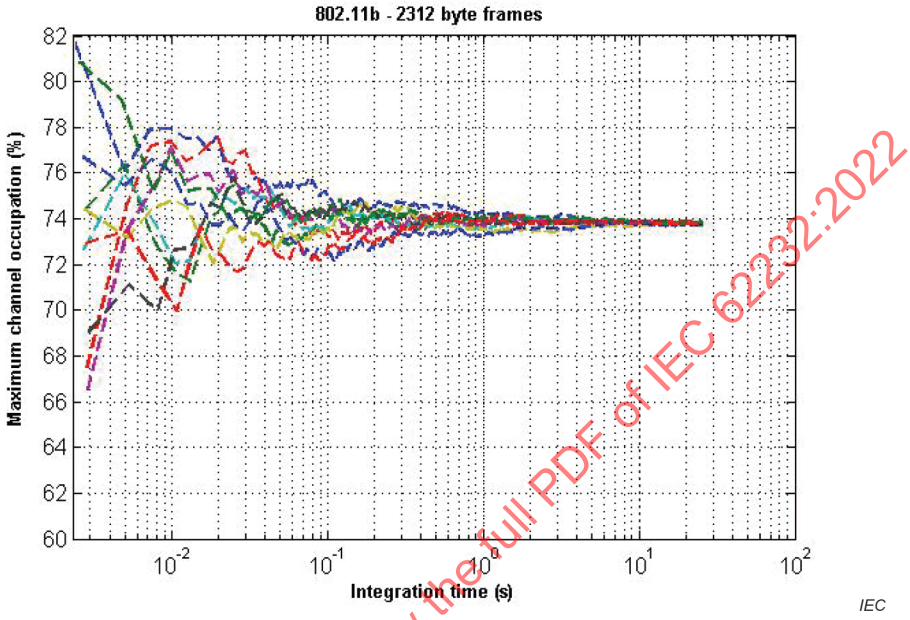


Figure E.5 – Channel occupation versus the integration time for IEEE 802.11b standard

E.6.3 Channel occupation

The packet transmission is done by encapsulating the IP packets into the MAC layer frames. These IP packets carry the application data and transport details from the upper layers and their size is not deterministic. Moreover, the size of the IP packets is usually not known *a priori* unless a controlled traffic generator is used. The objective is to calculate the emission time over a full observation time. Operating at a fixed maximum throughput, the length of the packets sent into the MAC layer is an important parameter to be determined. This length provides the variable time in which the channel is occupied. Figure E.6 shows how channel occupation varies with nominal throughput rate.

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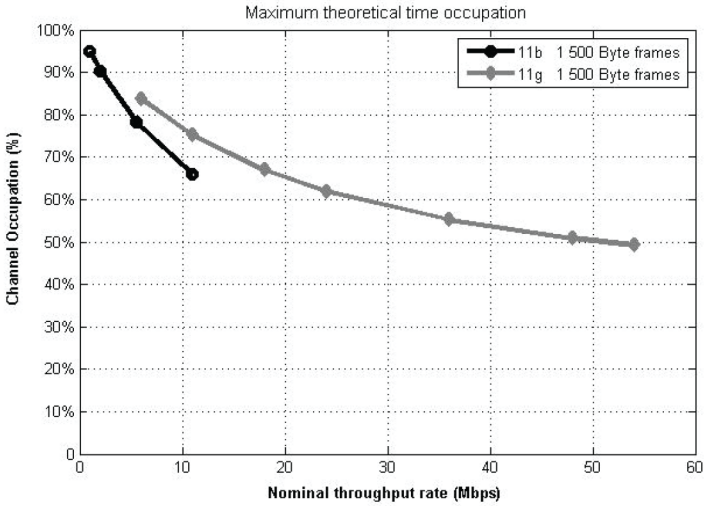


Figure E.6 – Channel occupation versus nominal throughput rate for IEEE 802.11b/g standards

E.6.4 Some considerations

Spectrum analysers are unable to plot the entire trace of a Wi-Fi signal even using the channel power process due to insufficient resolution bandwidth. The definition of analyser parameters can enhance plotting. However, due to the random separation between emissions, or packets, and the minimum sweeping time of the analyser, the plotted trace shows discontinuities while performing a measurement. In contrast, the resolution bandwidth of conventional equipment is an inverse function of the sweep time. An agreement between Wi-Fi channel bandwidth, resolution bandwidth, and the minimum sweep time to integrate the full emitted power, is not possible. Figure E.7 shows a snapshot of a Wi-Fi spectrum trace demonstrating a sweep with discontinuities due to transmission duration.

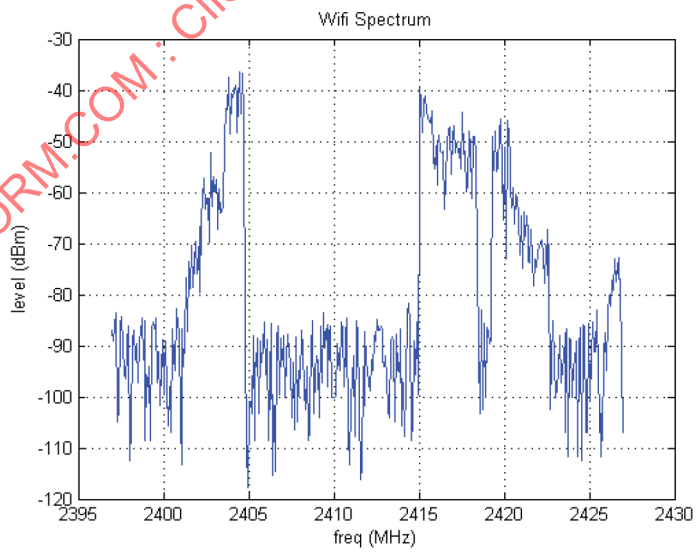


Figure E.7 – Wi-Fi spectrum trace snapshot

E.6.5 Measurement configuration and steps

The maximum output power can be measured either with a sensitive power meter or taking as reference the maximum-hold power trace. This trace would be multiplied by the occupation factor in order to get close to the real emitted power.

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Measurements of exposure from Wi-Fi with a spectrum analyser at an evaluation point require several steps to capture the Wi-Fi signal, convert measurements to integrated power density, and apply a duty-cycle factor. This technique has been adopted from [116].

a) Use a calibrated isotropic probe / antenna.
b) Set SA span to cover the Wi-Fi band or active channel(s).
c) Set SA resolution bandwidth to keep sweep less than or equal to 1 s.
d) Set SA to peak-hold function.
e) Record until the peak level stabilizes.
f) Convert spectral components to RF field strength.
g) Remove noise.
h) Integrate the result to determine power density.
i) Measure or estimate and apply duty-cycle factor.

Once the data has been collected and converted into power density, the noise from unoccupied spectrum scanned should be removed so it does not contribute to the integrated result. Remove the noise by zeroing spectral components below twice the baseline noise level interpolated just outside of the Wi-Fi band.

The integrated power density is calculated from the spectral components using Equation (E.10).

$$S_{\text{integrated}} = \frac{\Delta f}{1{,}055 \times \text{RBW}} \cdot \sum_i S_i \qquad \text{(E.10)}$$

where

$S_{\text{integrated}}$ is the integrated power density of the Wi-Fi signal;

Δf is the frequency spacing between stored spectral components, typically RBW/2;

RBW is the resolution bandwidth setting of the SA;

S_i is the power density of the i-th spectral component measuring signal after noise removal.

The integrated power density is a maximum or peak result and can be understood as maximum for exposure assessment. Consideration of the technology duty-cycle factor is required to assess actual exposure. Reference [117] describes a method using the zero-span function of a SA cantered on an active channel to determine duty-cycle at a particular time. A network analyser tool can also provide insight into duty-cycle.

E.6.6 Influence of the application layers

In ad-hoc networks the traffic can be increased to the maximum by streaming data packets from one computer to another using the UDP downlink protocol. UDP downlink offers a higher channel occupation than TCP by eliminating the error control and acknowledgement delays from the transport layer.

E.6.7 Power control

This technique is based on Wi-Fi operating at a fixed power. The most recent update to the Wi-Fi standard, IEEE 802.11ax, allows for power control. This affects results of the maximum measurements depending on the power control settings of the BS.

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E.7 LTE measurements

E.7.1 Overview

LTE mobile technology uses orthogonal frequency division multiplexing (OFDM) specified in 3GPP TS 36.104 to enhance the capacity related to the total data throughput [18], [111], [112] [113]. In 3GPP TS 36.211 [18], there are three types of frame structure for LTE. The frame structure type 1 is applicable to FDD, the frame structure type 2 is applicable to TDD, the frame structure type 3 is applicable to licensed assisted access (LAA).

E.7.2 LTE transmission modes

In LTE Release 9, the UE is semi-statically configured to receive PDSCH data transmissions in accordance with one of eight transmission modes, i.e. TM1 to TM8, as follows.

a) Transmission mode TM1: The scheme of PDSCH is single-antenna port transmission, using port 0. DCI format 1A of PDCCH can be used for common and UE specific, or format 1 for UE specific search space.

b) Transmission mode TM2: The scheme of PDSCH is diversity transmission. DCI format 1A of PDCCH can be used for common and UE specific, or format 1 for UE specific search space. For diversity scheme, the layer mapping should be done in accordance with different antenna ports and pre-coding for diversity is used in combination with layer mapping.

c) Transmission mode TM3: The scheme of PDSCH includes diversity and large delay CDD transmission. For diversity scheme, DCI format 1A of PDCCH can be used for common and UE specific search space. For diversity or large delay CDD scheme, DCI format 2A of PDCCH can be used for UE specific search space. For large delay CDD scheme, the layer mapping and pre-coding are different depending on the antenna ports.

d) Transmission mode TM4: The scheme of PDSCH includes diversity and closed-loop spatial multiplexing transmission. For diversity scheme, DCI format 1A of PDCCH can be used for common and UE specific search space. For diversity or closed-loop spatial multiplexing scheme, DCI format 2 of PDCCH can be used for UE specific search space. For closed-loop spatial multiplexing scheme, the layer mapping is the same as that of large delay CDD, but different for pre-coding.

e) Transmission mode TM5: The scheme of PDSCH includes diversity and multi-user MIMO transmission. For diversity, DCI format 1A of PDCCH can be used for common and UE specific search space. For multi-user MIMO, DCI format 1D of PDCCH can be used for UE specific search space, and the UE can assume that an eNodeB transmission on the PDSCH is performed on single layer.

f) Transmission mode TM6: The scheme of PDSCH includes diversity and closed-loop spatial multiplexing using a single transmission layer. For diversity, DCI format 1A of PDCCH can be used for common and UE specific search space. For closed-loop spatial multiplexing using a single transmission layer, DCI format 1B of PDCCH can be used for UE specific search space.

g) Transmission mode TM7: The scheme of PDSCH includes diversity and single-antenna port using port 0 or 5. For diversity or single-antenna port using port 0, DCI format 1A of PDCCH can be used for common and UE specific search space. For single-antenna port using port 5, DCI format 1 of PDCCH can be used for UE specific search space.

h) Transmission mode TM8: The scheme of PDSCH includes diversity, single-antenna port using port 0 or 7 or 8, dual layer transmission. For diversity or single-antenna port using port 0, DCI format 1A of PDCCH can be used for common and UE specific search space. For single-antenna port using port 7 or 8 and dual layer transmission, DCI format 2B of PDCCH can be used for UE specific search space. For the dual layer transmission scheme of the PDSCH, the UE can assume that an eNodeB transmission on the PDSCH is performed with two transmission layers on antenna ports 7 and 8.

Within a transmission mode, there are different transmission schemes which can be adopted depending on different wireless environment.

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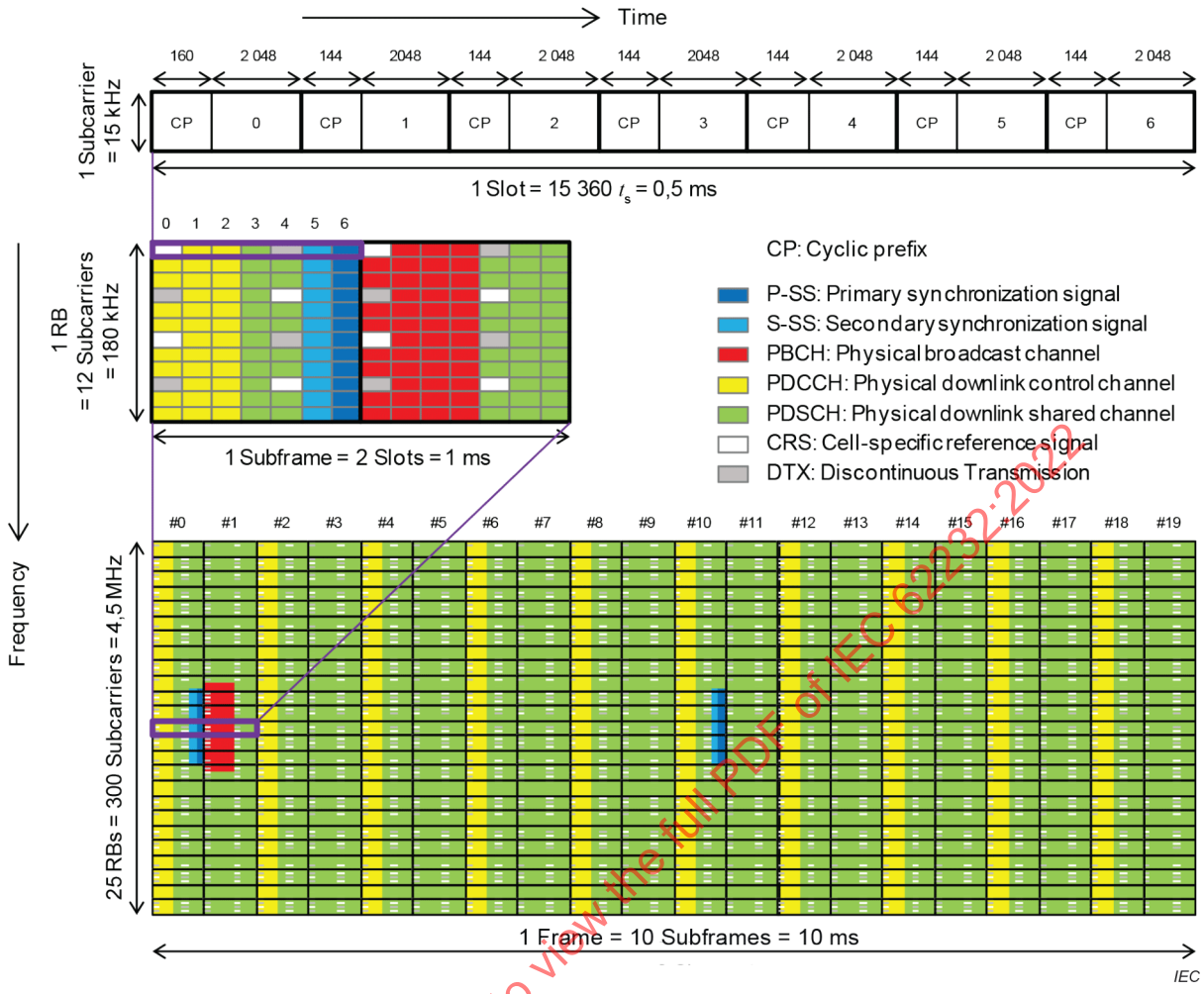
E.7.3 LTE-FDD frame structure

Figure E.8 shows the frame structure for the LTE FDD downlink signal based on 3GPP TS 36.211 [18]. The most recent release should be used, where relevant.

The frame in Figure E.8 is composed of resource elements (REs) consisting of one subcarrier in the frequency domain and one OFDM symbol in the time domain. The OFDM spacing between the individual subcarriers in LTE is 15 kHz. There is no frequency guard band between the subcarriers. The OFDM symbol consists of an effective data and a guard period called the cyclic prefix (CP) used in the time domain to prevent multipath interference. The LTE slot and subframe are 0,5 ms and 1 ms long in the downlink frame. In LTE, a normal and an extended CP length is possible resulting in seven or six OFDM symbols per slot, respectively. A resource block (RB) consists of 12 subcarriers, with a total bandwidth of 180 kHz, and is transmitted for the duration of one LTE slot. Transmission bandwidth configurations between six and 100 RBs are possible, corresponding to a channel bandwidth between 1,4 MHz and 20 MHz, as shown in Table E.10.

As for other land mobile radio systems, the total transmission power of an LTE base station depends on the amount of communication traffic. The power level reaches the designed maximum power when the amount of communication traffic is at maximum. Two types of evaluation methods for LTE exposure levels based on measurement are given in E.7.4 and E.7.6. E.7.4 describes evaluation methods for assessing the maximum exposure level using two methods of measurement and extrapolation. E.7.6 describes an evaluation method for assessing the instantaneous exposure level.

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NOTE Different time intervals are defined as multiples of a basic time unit t_s = 1/30 720 000 s.

Figure E.8 – Frame structure of transmission signal for LTE-FDD downlink

E.7.4 LTE-TDD frame structure

The frame structure is shown in Figure E.9 and Figure E.10. Type 2 is applicable to TDD. Each radio frame of length T_f = 30 720 × T_s = 10 ms consists of two half-frames of length 153 600 × T_s = 5 ms each. Each half-frame consists of five subframes of length 30 720 × T_s = 1 ms.

The supported uplink-downlink configurations are listed in Table E.9, where, for each subframe in a radio frame, "D" denotes the subframe is reserved for downlink transmissions, "U" denotes the subframe is reserved for uplink transmissions and "S" denotes a special subframe as described in [18]. Each subframe i is defined as two slots, $2i$ and $2i$ +1 of length T_{slot} = 15 360 × T_s = 0,5 ms in each subframe.

Uplink-downlink configurations with both 5 ms and 10 ms downlink-to-uplink switch-point periodicity are supported. In case of 5 ms downlink-to-uplink switch-point periodicity, the special subframe exists in both half-frames. In case of 10 ms downlink-to-uplink switch-point periodicity, the special subframe exists in the first half-frame only.

In case multiple cells are aggregated, the UE can assume the same uplink-downlink configuration across all the cells and that the guard period of the special subframe in the different cells has an overlap of at least 1 456 × T_s.

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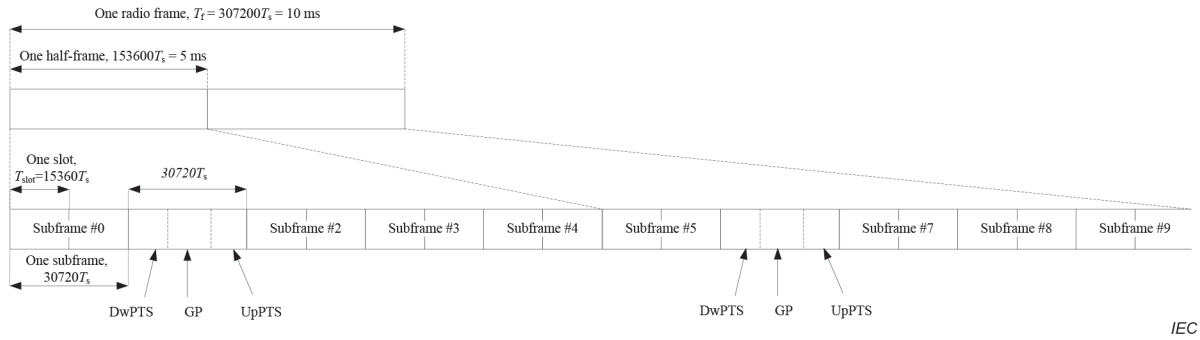
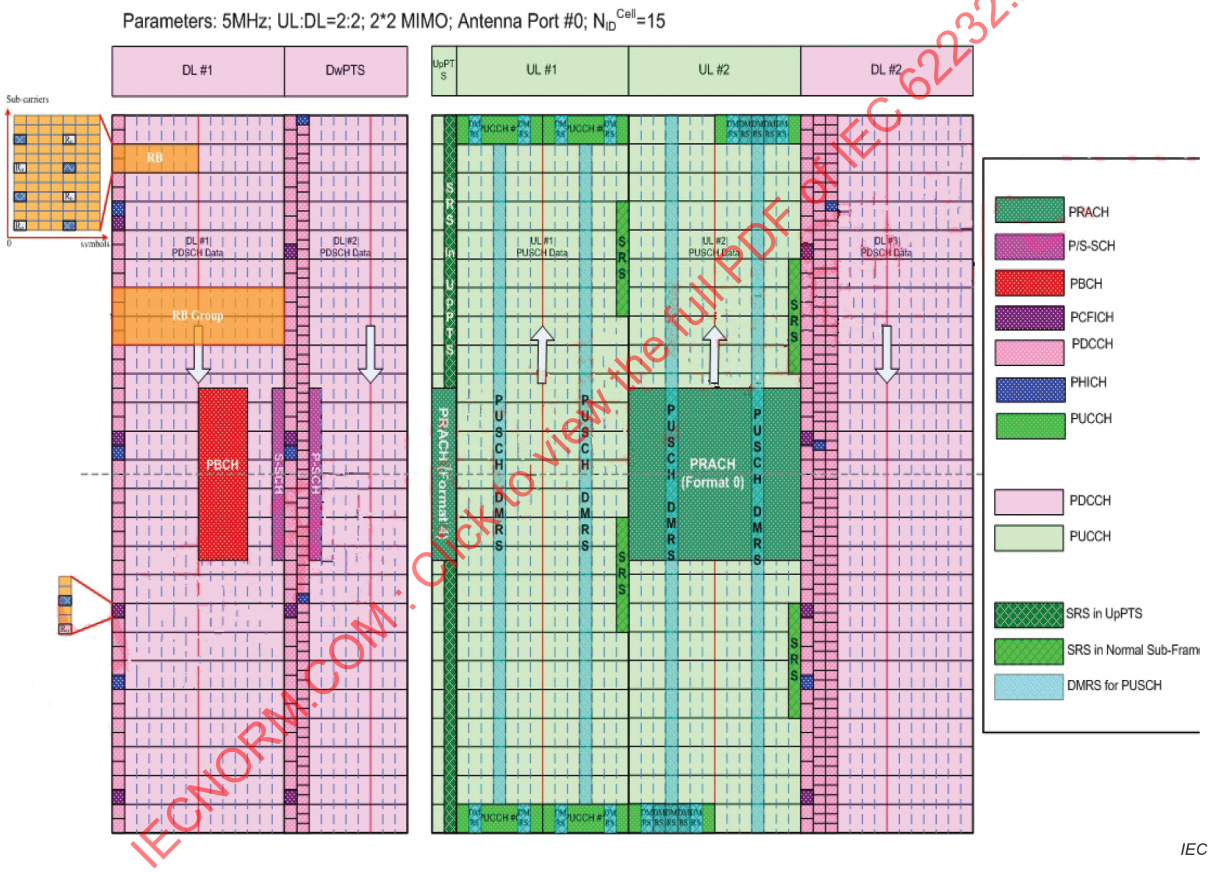


Figure E.9 – Frame structure LTE-TDD type 2 (for 5 ms switch-point periodicity)



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Figure E.10 – Frame structure of transmission signal for LTE-TDD

Table E.9 – Uplink-downlink configurations

Uplink-downlink configuration	Downlink-to-uplink switch-point periodicity	Subframe number									
		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

E.7.5 Maximum LTE exposure evaluation

E.7.5.1 General

Two extrapolation methods used to assess the maximum exposure level from an LTE base station are provided. E.7.5.2 describes an evaluation method using a dedicated decoder. E.7.5.3 describes an evaluation method using a spectrum analyser. Both methods can be used, but in environments with strong selective fading or when evaluating each exposure level from multiple base stations accurately the method using a dedicated decoder is recommended.

To evaluate the exposure level for maximum traffic conditions by extrapolation, it is important that the transmitted power of the received signal or channel is not dependent on the amount of traffic. As their power levels are constant, time invariant signals such as the reference signal (RS), the Primary Synchronization Signal (P-SS), the Secondary Synchronization Signal (S-SS), or the physical broadcast channel (PBCH) can be used for the extrapolation-based evaluation method. The RS is well suited for this because the locations of the LTE reference signals (RSs) are uniformly distributed over the occupied radio bandwidth to reduce effects of frequency selective fading. The RS represents the cell-specific reference signal (CRS), which is one type of reference signal.

The methods described in E.7.5.2 and E.7.5.3 apply if the radiation pattern and the power per resource element (RE) for the RS are the same as for the traffic channels (or any other signal transmitted by the EUT). Otherwise, an additional extrapolation factor should be considered in the extrapolation to account for the possible difference in the antenna gain and power as described in B.8.5.

E.7.5.2 Method using a dedicated decoder

In this method, the RF field strength corresponding to the RS [9] of an LTE cell is measured. If multiple antennas are used for transmission by the same cell (MIMO), the RS should be determined for each antenna (or antenna port). This type of measurement requires dedicated LTE decoders or LTE analysers.

The measurements require that the system bandwidth and centre frequency of the target LTE carrier is set. The maximum electric field strength (V m^{-1}), E_{asmt}, is specified in Equation (E.11).

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9 The RS RF field strength is measured as the linear average over the RF field strength contributions of all resource elements that carry the RS within the operating bandwidth. Thus, the measured value corresponds to the average power transmitted for one subcarrier.

$$E_{\text{asmt}} = E_{\text{RS}} \cdot \sqrt{N_{\text{RS}} \cdot F_{\text{TDC}} \cdot F_{\text{B}}^{-1}} \quad \text{(E.11)}$$

where

E_{RS} is the field level (V m^{-1}) of the RS per resource element (RE);

N_{RS} is the extrapolation factor for the RS, which is the ratio of the maximum transmission power to the transmission power corresponding to the RS per RE;

F_{B} is the boosting factor for the RS;

F_{TDC} is the technology duty-cycle factor.

In the case of a MIMO antenna system, operated with large-delay cyclic delay diversity (CDD) or Tx diversity, Equation (E.11) is modified as in Equation (E.12).

$$E_{\text{asmt}} = \sqrt{\sum_i E_{\text{RS},i}^2} \cdot \sqrt{N_{\text{RS}} \cdot F_{\text{TDC}} \cdot F_{\text{B}}^{-1}} \quad \text{(E.12)}$$

where $E_{\text{RS},i}$ is the electric field strength (V m^{-1}) from the i-th branch of the MIMO antenna and the sum is taken over all branches.

In this circumstance, it is assumed that the transmitted fields associated with each branch are uncorrelated, see E.7.4. This value can be obtained from the network operator.

Considering the frame structure for the LTE downlink described in E.7.1, N_{RS} corresponds to the number of subcarriers for the system bandwidth of the target base station. The theoretical extrapolation factor, N_{RS}, for each system bandwidth is shown in Table E.10, provided all subcarriers are at the same power level.

RS power per resource element measurement example is shown in Figure E.11.

Table E.10 – Theoretical extrapolation factor, N_{RS}, based on frame structure given in 3GPP TS 36.104 [21]

Channel bandwidth (MHz)	Number of resource blocks	Transmission bandwidth (MHz)	N_{RS} = extrapolation factor for RS (linear/dB)
1,4	6	1,08	72 / 18,57
3	15	2,7	180 / 22,55
5	25	4,5	300 / 24,77
10	50	9,0	600 / 27,78
15	75	13,5	900 / 29,54
20	100	18,0	1 200 / 30,79

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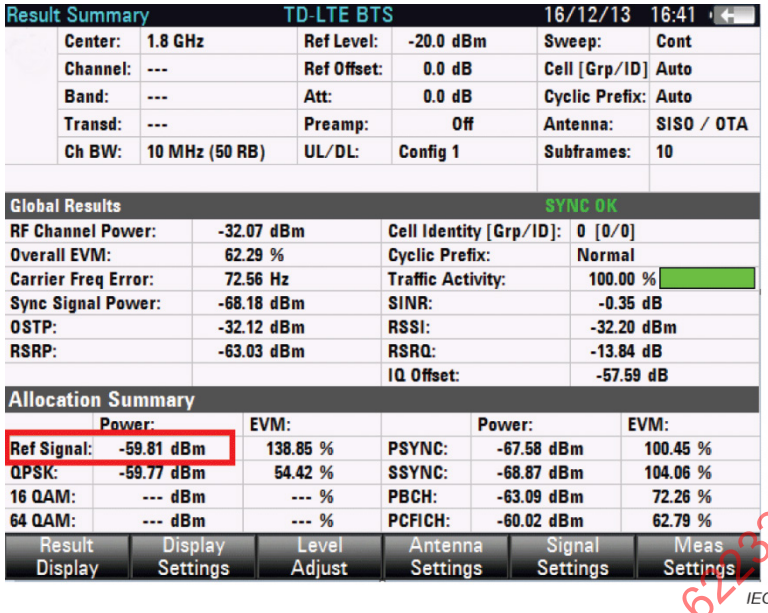


Figure E.11 – LTE-TDD PBCH measurement example

E.7.5.3 Method using a basic spectrum analyser

A basic spectrum analyser (SA) is less expensive and more commonly available than a dedicated LTE decoder. However, when using a basic SA, the powers of the RSs cannot be accurately detected because they are transmitted on single resource elements spread in frequency and time.

To overcome this issue and to avoid any requirement for prior knowledge regarding band occupation or service characteristics, the PBCH power can be measured. The PBCH is transmitted with the same characteristics regardless of the configuration or service bandwidth and spans a bandwidth of six RBs (approximately 1 MHz) over the centre frequency of the LTE signal.

NOTE The signal from each LTE base station cannot be identified using this method due to frequency spectrum overlapping.

The following SA configuration recommendations apply when performing the PBCH measurement.

a) The centre frequency of the spectrum analyser should be aligned with the centre frequency of the LTE signal.

b) The frequency span should be set to zero (scope mode) in order to measure the received time signal for the downlink emission frequency.

c) A resolution bandwidth (RBW) of 1 MHz should be set to integrate the signal over the PBCH spectral spread.

d) In order to obtain an integration time close to the symbol duration of each pixel on the screen of the SA, the sweep time should be set equal to approximately the product of the number of display points of the SA and the symbol duration (approximately 70 µs), e.g. a sweep time of approximately 70 ms for an SA with 1 000 display points (or equivalent ratio for instruments with lower display resolution).

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e) The detector should be set to root-mean-square (RMS) mode; if the detector cannot be set to "RMS" mode, it can be set to "sample" or "peak" mode.

   1) When using "sample" or "peak" detector mode, VBW smaller than the RBW should be used to avoid overestimation due to signal fluctuation. On the other hand, the VBW should be widened so that the transient time of the video filter is shorter than the duration of the target signal (PBCH, P-SS and S-SS) to avoid underestimation. If the time constant of the video filter is T_{video} (T_{video} = 1/(2π·VBW)), the transient time to obtain 95 % of the voltage is 3 × T_{video}. Therefore, in order to reduce the uncertainty while avoiding underestimation, VBW should be the smallest value with a transient time (3 × T_{video}) smaller than the duration of the measured signal (PBCH, P-SS and S-SS). VBW examples are provided in Figure E.12, 3 kHz for LTE using a RBW of 1 MHz.

   2) When using "RMS" detector mode, the VBW should either be equal to or greater than the RBW, or switched off to avoid underestimation.

f) The trace type should be set to maximum hold using a minimum sweep time of 20 s; alternatively, a 10 ms (i.e. the length of an LTE radio frame) trigger should be applied in order to prevent trace fluctuations along the time axis and to prevent that other channels in the frame, transmitted with a higher power, saturate the trace in maximum hold.

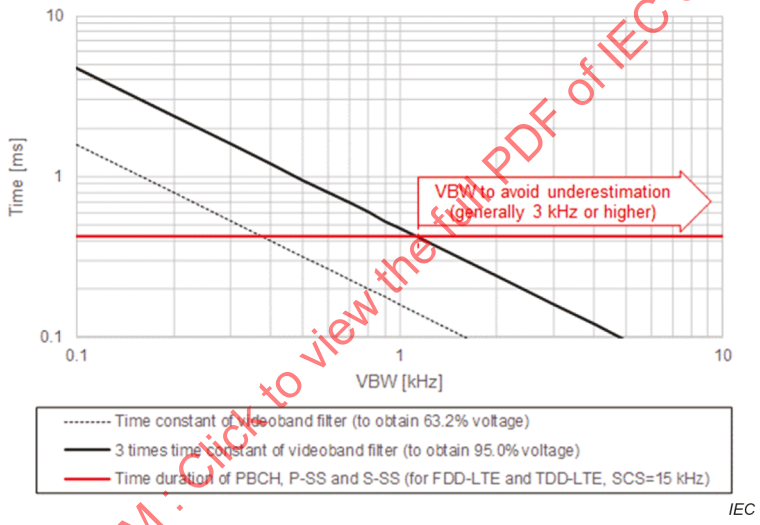


Figure E.12 – Example of VBW setting for LTE-FDD and LTE-TDD to avoid underestimation

In order to use the RMS detector, the maximum power should be effectively allocated to the PBCH channel.

The boosting factor F_B should be included as defined in Equation (E.12).

The measured peak power, P_{PBCH}, corresponds to the received PBCH signal power over the bandwidth of six RBs (72 subcarriers). The electric field strength of the PBCH signal, E_{PBCH}, is determined from P_{PBCH}. The extrapolated maximum electric field strength, E_{asmt}, of the LTE signal at each evaluation location is given by Equation (E.13).

$$E_{asmt} = E_{PBCH} \cdot \sqrt{N_{PBCH} \cdot F_{TDC}} \quad \text{(E.13)}$$

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where N_{PBCH} is the extrapolation factor for the PBCH, which is the ratio of the maximum transmission power to the transmission power corresponding to the PBCH over six RBs. N_{PBCH} can be provided by the network operator or can be calculated theoretically in accordance with Equation (E.14).

$$N_{PBCH} = \frac{N_{RS}}{72} \tag{E.14}$$

where N_{RS} denotes the number of subcarriers in the used transmission bandwidth, see Table E.10.

Figure E.13 shows measurement examples of an LTE-FDD downlink signal using the spectrum analyser with a zero span, 550 sampling points, a sweep time of 39 ms (70 µs × 550), and the resolution bandwidth of 1 MHz. Figure E.13 (a) and (b) show the results for low and medium traffic level environments with a single sweep, respectively. Figure E.13 (c) shows the received signal after the sweep of 20 s regardless of the amount of traffic.

For measuring LTE-TDD, the powers of the RSs cannot be accurately detected using a basic spectrum analyser as they are transmitted on single resource elements spread in frequency and time. It is difficult to directly detect the power of the RSs, however the PBCH can be measured using a spectrum analyser and extrapolation factor for the PBCH. A spectrum analyser cannot distinguish uplink signals from downlink signals in TDD mode when used in the frequency domain. The spectrum analyser cannot distinguish PBCH signal from PRACH; therefore, in general, the SA method for FDD case cannot be applied to TDD case. However, if the evaluation is performed close to base station and away from UEs, the signals from UEs can be neglected. In this case, the SA method can be applied to TDD case. However, a spectrum analyser can indeed distinguish uplink signals from downlink signals when a periodic trigger on the zero-span trace is properly set. In order to detect PBCH in TDD with a spectrum analyser, it is recommended to verify that any mobile phone nearby is at a distance from the measurement point such that the uplink contribution received is not comparable with downlink contribution.

Figure E.14 shows measurement examples of PBCH power with spectrum analyser using zero span.

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Figure E.13 – Examples of received waves from LTE-FDD downlink signals using a spectrum analyser using zero span mode

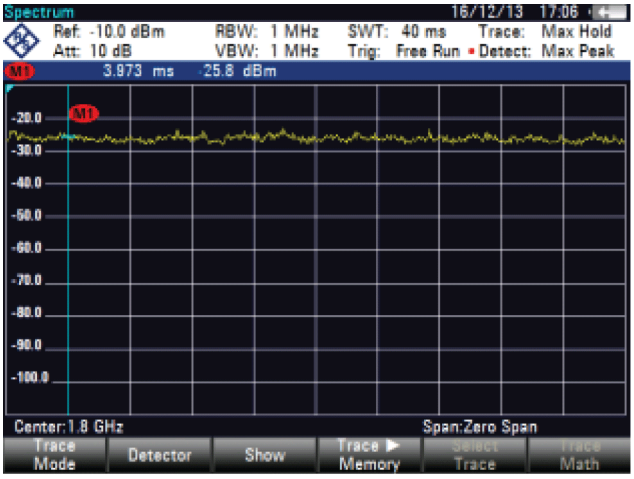


Figure E.14 – LTE-TDD PBCH measurement example spectrum analyser using zero span mode

E.7.5.4 Method for beamforming antennas

If the radiation pattern of the RS is different from that of other signals transmitted by the EUT (e.g. traffic channels), the extrapolation factor should take into account the possible difference in the antenna gain, such that maximum possible RF field strength is obtained. The extrapolated maximum electric field strength (V m^{-1}), E_{asmt}, is defined by Equation (E.15).

$$E_{asmt} = E_{RS} \cdot \sqrt{N_{RS} \cdot F_{extBeam} \cdot F_{TDC} \cdot F_B^{-1}} \quad \text{(E.15)}$$

where

E_{RS} is the field level (V m^{-1}) of the RS per RE;

N_{RS} is the extrapolation factor for the RS, which is the ratio of the maximum transmission power to transmission power corresponding to the RS per RE;

F_B is the boosting factor for the RS;

F_{TDC} is the technology duty-cycle;

$F_{extBeam}$ is the extrapolation factor corresponding to the ratio of the traffic EIRP envelope to the broadcast EIRP envelope in the direction of the evaluation location.

E.7.6 Instantaneous LTE exposure evaluation

For the appropriate settings of measurements of momentary or instantaneous LTE exposure, an SA and suitable antenna probes are needed.

The SA settings can have a significant influence on the measurement results. It is critical that optimal settings to perform RF exposure evaluation of LTE signals are determined and recorded. The following settings to perform exposure evaluation for LTE are proposed in [118]: RMS detector, resolution bandwidth (RBW) = 1 MHz, sweep time = 20 s, and appropriate selection of the frequency span, e.g. 50 MHz. These settings were determined and tested in the laboratory and in-situ [118].

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E.7.7 MIMO multiplexing of LTE BS

LTE introduces multiple input multiple output (MIMO) multiplexing to increase the system capacity and data throughput. When conducting an exposure evaluation, the multiple RF sources should be considered. If four-layer MIMO multiplexing is employed, the number of RF sources is equal to four on the same RF frequency band. IEC TR 62630 [41] describes a method for combining multiple RF sources. The combination method depends heavily on the correlation between the RF sources. There are some options for LTE regarding the MIMO transmission mode, i.e. Tx diversity, large-delay CDD, and closed-loop spatial multiplexing. In [119], no correlation between the fields associated with different MIMO branches employed in large-delay CDD or Tx diversity was observed. In this transmission mode, the simple power sum method is applicable as the combination method to evaluate the total RF field strength as described in IEC TR 62630 [41]. On the other hand, if a correlation between the signals from MIMO branches is found, applying the first or second conservative method given in IEC TR 62630 [41] should be considered to evaluate the total RF field strength.

If extrapolation is performed in accordance with Equation (E.12), the effect of correlation among the antenna branches is already considered by F_{extBeam}.

E.8 NR BS measurements

E.8.1 General

The minimum RF characteristics and minimum performance requirements of NR BS are described in 3GPP TS 38.104 [17] and physical channels and modulation are specified in 3GPP TS 38.211 [19].

To evaluate the exposure level for maximum traffic conditions by extrapolation, it is important that the transmitted power of the received signal or channel is not dependent on the amount of traffic. As defined in 3GPP TS 38.211 [19], the primary synchronization signal (PSS), the secondary synchronization signal (SSS), the physical broadcast channel (PBCH) and the channel state information reference signal (CSI-RS) can be used as the stable reference signal in the extrapolation-based evaluation method, because the power levels are constant. PSS, SSS, PBCH and PBCH-DMRS (i.e. SSB) are always available and extrapolation method applies always for every NR BS.

The CSI-RS signals are not necessarily present (e.g. if there is no connected UE) and configured in a way that is suitable for extrapolation. Therefore, CSI-RS based extrapolation only applies when a special mode is enabled by the EUT.

NOTE The evaluation of exposure level based on maximum traffic conditions using extrapolation might not be suitable when the base station is implemented with power limiting features, see for example [120].

E.8.2 Maximum NR exposure evaluation

E.8.2.1 NR signal extrapolation based on SSB

E.8.2.1.1 General

The evaluation methods described in E.8.2.1 are based on extrapolation to assess the maximum exposure level from an NR base station using SSS, PSS, PBCH or PBCH-DMRS signal (i.e. the SSB). E.8.2.1.2 describes an evaluation method using a dedicated decoder. E.8.2.1.3 describes an evaluation method using a spectrum analyser. Both methods can be used and they differ only in the way the time invariant component of the NR signal is measured, see details in [121], [122] and [123]. While, in general, SSB based extrapolation is possible, only decoding of the SSS allows for extrapolation of maximum exposure for each cell ID separately.

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The methods described in E.8.2.1.2 and E.8.2.1.3 apply if the radiation pattern and the power per resource element (RE) for the SSB are the same as for the traffic channels (or any other signal transmitted by the EUT). Otherwise, an additional extrapolation factor should be considered in the extrapolation to account for the possible difference in the antenna gain and power as described in B.8.5.

E.8.2.1.2 Method using a dedicated NR decoder

In this method, the RF field strength corresponding to the SSB of an NR BS is measured by means of dedicated NR decoders or NR analysers.

The measurements require that the system bandwidth and centre frequency of the target NR carrier are set. The extrapolated electric field strength (V m^{-1}), E_{asmt} is defined by Equation (E.16).

$$E_{\text{asmt}} = E_{\text{SSB}} \cdot \sqrt{F_{\text{extSSB}}} = E_{\text{SSB}} \cdot \sqrt{F_{\text{BW}} \cdot F_{\text{PR}} \cdot F_{\text{TDC}} \cdot F_{\text{B}}^{-1}} \quad \text{(E.16)}$$

where

E_{SSB} is the measured electric field level (V m^{-1}) per resource element (RE) of the strongest SSB (corresponds to $E_{\text{broadcast}}$ in Equation (B.59));

F_{TDC} is the technology duty-cycle;

F_{PR} is the power reduction if the actual maximum approach is used, otherwise it is set to 1;

F_{B} is the ratio of the power transmitted for the SSB symbol to the traffic symbol (boosting factor). F_{B} is set to 1 if the power for the SSB and traffic symbols is the same or if the difference in power is already factored in F_{extBeam}.

F_{BW} is the ratio of the total carrier bandwidth and the subcarrier frequency spacing of the SSB;

F_{extSSB} is the extrapolation factor for the SSB.

When the power allocated to any subcarrier is the same, F_{BW} corresponds to the number of resource elements for the EUT, see [118]. The extrapolation factor, F_{BW}, for each system bandwidth is shown in Table E.11 and Table E.12 assuming that all subcarriers are transmitted with the same power level.

Table E.11 – F_{BW} for each combination of BS channel bandwidth and SSB subcarrier spacing (SCS) for sub-6 GHz signals

SCS	Bandwidth (MHz)												
[kHz]	5	10	15	20	25	30	40	50	60	70	80	90	100
15	300	624	948	1 272	1 596	1 920	2 592	3 240	n/a	n/a	n/a	n/a	n/a
30	132	288	456	612	780	936	1 272	1 596	1 944	2 268	2 604	2 940	3 276
60	n/a	132	216	288	372	456	612	780	948	1 116	1 284	1 452	1 620
n/a = not applicable.													

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Table E.12 – F_{BW} for each combination of BS channel bandwidth and SSB subcarrier spacing (SCS) for mm-wave signals

SCS [kHz]	Bandwidth (MHz)			
	50	100	200	400
60	792	1 584	3 168	n/a
120	384	792	1 584	3 168
n/a = not applicable.				

In order to distinguish between the contribution of different cells E_{SSB} should correspond to the RF field strength per RE of the decoded SSS.

E.8.2.1.3 Method using a spectrum analyser

E.8.2.1.3.1 SSB mapping

This method is similar to E.8.2.1.2 with the difference that E_{SSB} is measured by means of a spectrum analyser (SA). Since the SSB is spread in time, when using a SA, the power of the RE SSB cannot be directly assessed but it requires post-processing in order to identify the resources allocated to the SSB (based on its periodicity and duration) [123].

The following SA configuration parameter recommendations apply for the measurement of the SSB power per RE.

a) The centre frequency of the spectrum analyser should be equal to the centre frequency of the SSB.

b) The frequency span should be set to zero (scope mode) in order to measure the received time signal for the SSB.

c) The resolution bandwidth (RBW) should be set smaller than 127 sub-carriers (e.g. 1 MHz). The wider the RBW, the more REs are measured to obtain an accurate average value per RE.

d) The detector should be set to root mean square (RMS) mode; if the detector cannot be set to "RMS" mode, it can be set to "sample" or "peak" mode.

   1) When using "sample" or "peak" detector mode, a VBW smaller than the RBW should be used to avoid overestimation due to signal fluctuation. On the other hand, the VBW should be widened so that the transient time of the video filter is shorter than the duration of the target signal (PBCH, P-SS and S-SS) to avoid underestimation. If the time constant of the video filter is T_{video} (T_{video} = 1/(2π·VBW)), the transient time to obtain 95 % of the voltage is 3 × T_{video}. Therefore, in order to reduce the uncertainty while avoiding underestimation, VBW should be the smallest value with a transient time (3 × T_{video}) smaller than the duration of the measured signal (SSB). VBW examples are provided in Figure E.15, 10 kHz for NR FR1 with SCS of 30 kHz using a RBW of 1 MHz and 30 kHz for NR FR2 with SCS of 120 kHz using a RBW of 1 MHz. Examples of the impact of VBW on accuracy are provided in Figure E.16. The exact settings can be adjusted depending on the SA type, see Figure C.3.

   2) When using "RMS" detector mode, the VBW should either be equal to or higher than the RBW or switched off to avoid underestimation.

e) The sweep time should be equal to approximately the product of the number of display points of the SA and the symbol duration in order to obtain an integration time close to the symbol duration of each pixel on the screen of the SA.

f) A factor of $\sqrt{SCS / RBW}$ should be applied to the measured field value in order obtain the RF field strength per RE.

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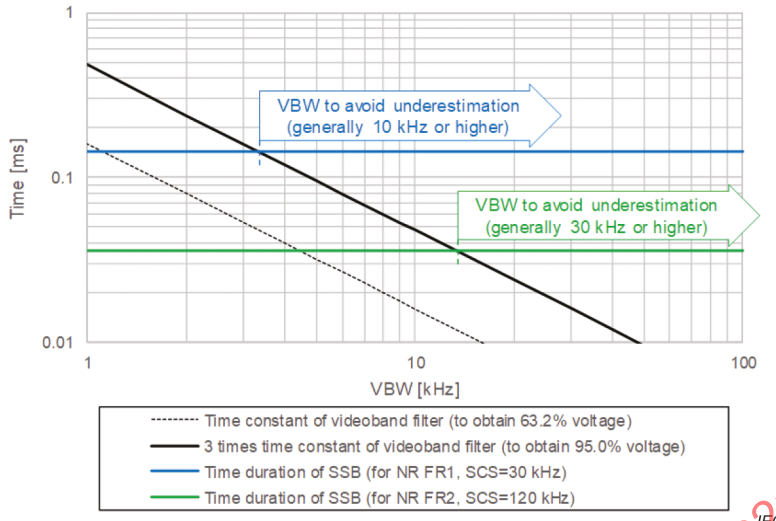


Figure E.15 – Example of VBW setting for NR to avoid underestimation

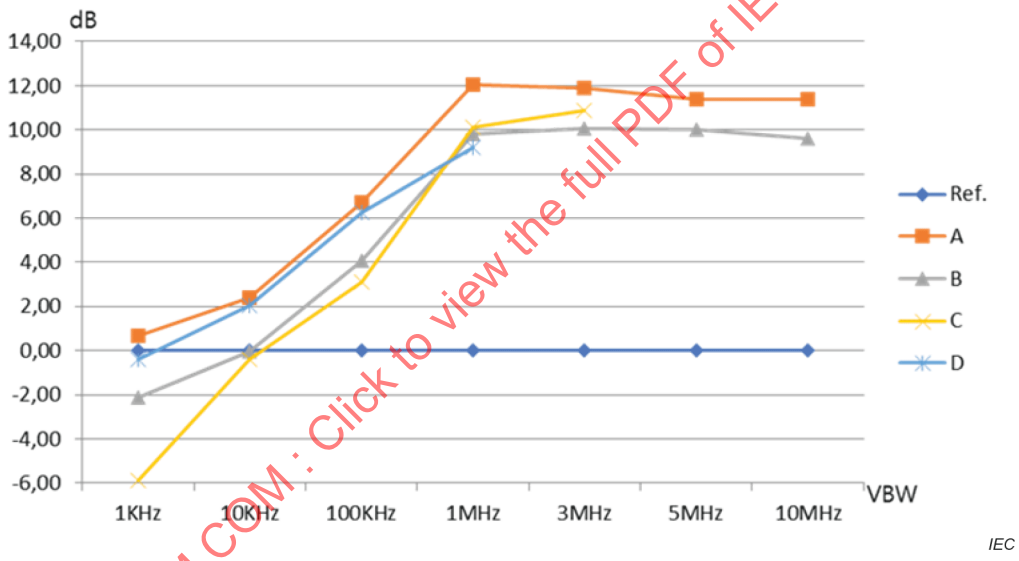
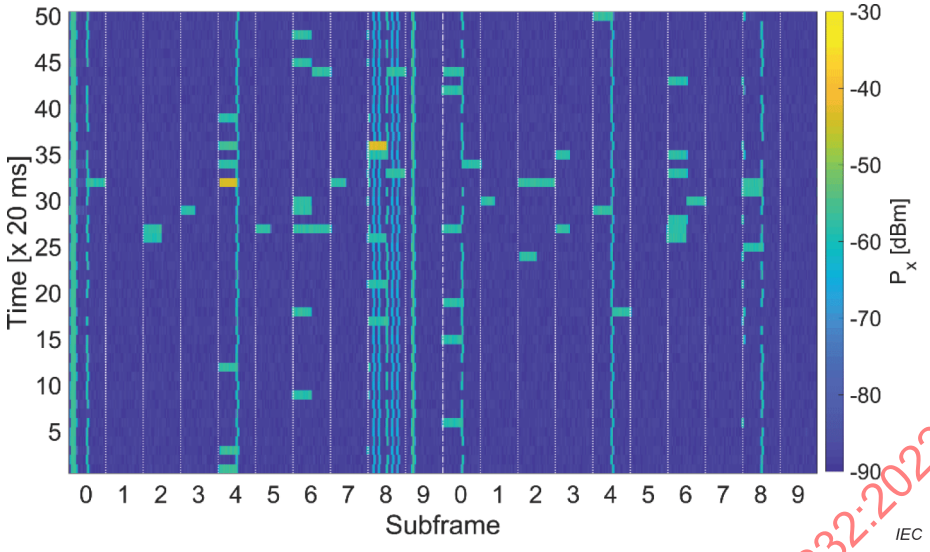


Figure E.16 – Examples of measurement accuracy results according to the ratio of VBW and RBW for NR SCS 30 kHz and 1 MHz RBW using various SA types (A to D)

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The diversity and periodicity of the NR signal components in the measured bandwidth can be visualized by arranging the measured RE samples over time in accordance with the SSB periodicity as described in detail in [123]. Since the SSB is transmitted with a specific periodicity, duration and at a constant power level, this can be distinguished from the other signals (e.g. traffic) and its field strength per RE evaluated.

An example is given in Figure E.17.



NOTE The colour of the pixel depicts the root mean square (RMS) received power within a 1 MHz bandwidth around the centre frequency of the SSB during a measuring time of 35,68 µs. Stacked on top of each other (i.e. along the y-axis) are consecutive 20 ms measurement periods, i.e. two NR radio frames of 10 ms, which are divided into subframes along the x-axis. The signal observed in subframe 0 of each first frame has a constant power level, a periodicity of 20 ms, and a length of four pixels or four OFDM symbols in the case of a signal with SCS 30 kHz. This signal represents the SSB.

Figure E.17 – Waterfall reconstruction plot of a 1 s long measurement trace of an NR signal with subcarrier spacing (SCS) 30 kHz (along one component of the electric field)

E.8.2.1.3.2 SSB gating

This method makes use of the triggering and gating functions of spectrum analysers to measure E_{SSB}. It applies when the SSB power or RF field strength level in the measured bandwidth is higher than the PDSCH. When measuring the NR frame with a SA, it is important to get a stable measurement. If the SSB signal level is above PDSCH , the rising edge trigger (e.g. the first SSB signal as shown in Figure E.18) can be used to detect the peak SSB level on the SA using zero span to get stable NR signals (e.g. mark on SSB in Figure E.18).

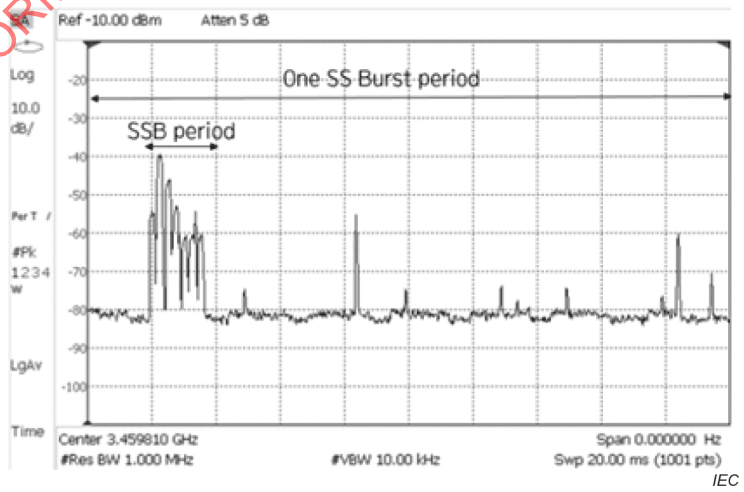


Figure E.18 – Example of NR signal frame measured on SA with SSB signal above PDSCH (data)

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The detector should be set to root mean square (RMS) mode. If the detector cannot be set to "RMS" mode, it can be set to "sample" or "peak" mode.

- When using "RMS" detector mode, the VBW should either be equal to or higher than the RBW or switched off to avoid underestimation.
- When using "sample" or "peak" detector mode, a VBW smaller than the RBW should be used to avoid overestimation due to signal fluctuation. On the other hand, the VBW should be widened so that the transient time of the video filter is shorter than the duration of the target signal (PBCH, P-SS and S-SS) to avoid underestimation. If the time constant of the video filter is T_{video} (T_{video} = 1/(2π·VBW)), the transient time to obtain 95 % of the voltage is 3 × T_{video}. Therefore, in order to reduce the uncertainty while avoiding underestimation, VBW should be the smallest value with a transient time (3 × T_{video}) smaller than the duration of the measured signal (SSB). VBW examples are provided in [124]

In some situations, the SSB signal from the measured BS can be lower than the other existing signals, for example in case of fully loaded PDSCH or interference from other BS. In such case, the rising edge trigger does not necessarily provide stable SSB measurements. In this case, the "time-gating" function can be configured in accordance with the SSB periodicity (e.g. 10 ms), see Figure E.19. The "time gating" function isolates a portion of a time record for further viewing and analysis. Time gating is often used to analyse non-stationary signals or portions of stationary signals such as burst signals from TDMA communication bursts.

NOTE Multiple terms can be used by SA manufacturers for the "time gating" function, for example "time trigger" or "gate trigger".

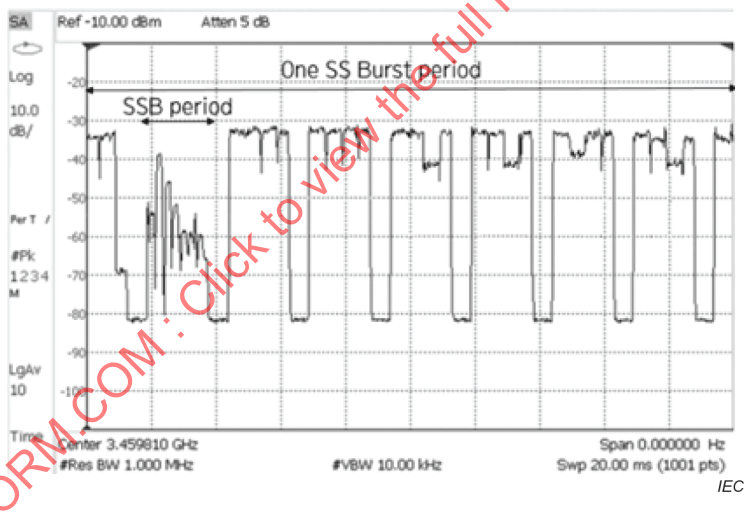


Figure E.19 – Example of NR signal frame measured on SA with SSB signal below or equal to PDSCH (data)

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The SSB power per RE should be measured using the gating function of the SA as follows.

a) Set the SA centre frequency to the same value as the centre frequency of the SS block frequency position provided by the NR BS operator or using an automatic discovery process leveraging the global synchronization channel number (GSCN) and the NR absolute radio frequency channel number (NR-AFCN) as defined in 3GPP 38.104 [17].

b) Set the SA resolution bandwidth (RBW) equal to SSB bandwidth (e.g. 7,2 MHz considering 240 RE of 30 kHz); if SA does not support the required RBW, it can be set to 1 MHz.

c) Configure the SA in "trigger mode" and "zero span".

d) Activate the SA trigger mode "time trigger" or "gate trigger".

e) Set the "trigger time" or "time gating length" to the same value as the "SS burst period" in the NR BS (e.g. 5 ms, 10 ms, 20 ms, 40 ms, 80 ms or 160 ms), see Figure E.20.

f) Measure the peak level of the trace.

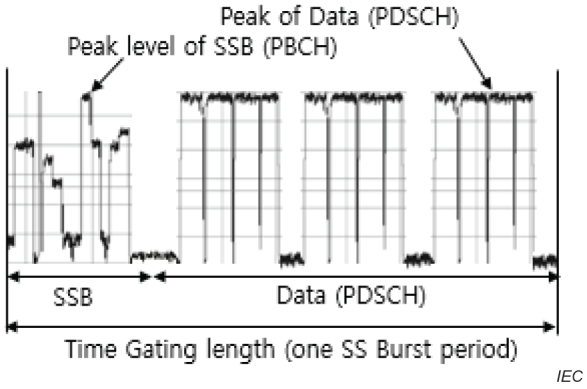


Figure E.20 – Time gating of SS burst signal

A factor $\sqrt{SCS / RBW}$ is applied to the measured field value in order obtain the RF field strength per RE.

As an example, in case of 100 MHz and 80 MHz with 30 kHz SCS:

- Channel BW = maximum transmission bandwidth + guard bands on both sides, see Figure E.21
- Channel Bandwidth(CBW) =
  [Number of RB × Number of Subcarrier × SCS + Guard Band × 2]
  = 273 × 12 × 30 kHz + (845 × 2) = 99,970 kHz
  = 217 × 12 × 30 kHz + (925 × 2) = 79,970 kHz

When implementing such time domain measurements:

- it is not possible to distinguish signals from multiple NR BS using the SA, therefore the predominant NR BS should be identified by other means (e.g. distance);
- the peak marker is sometimes automatically placed on PDSCH area, resulting in overestimated results, therefore it is recommended to check that the marker remains at the SSB area.

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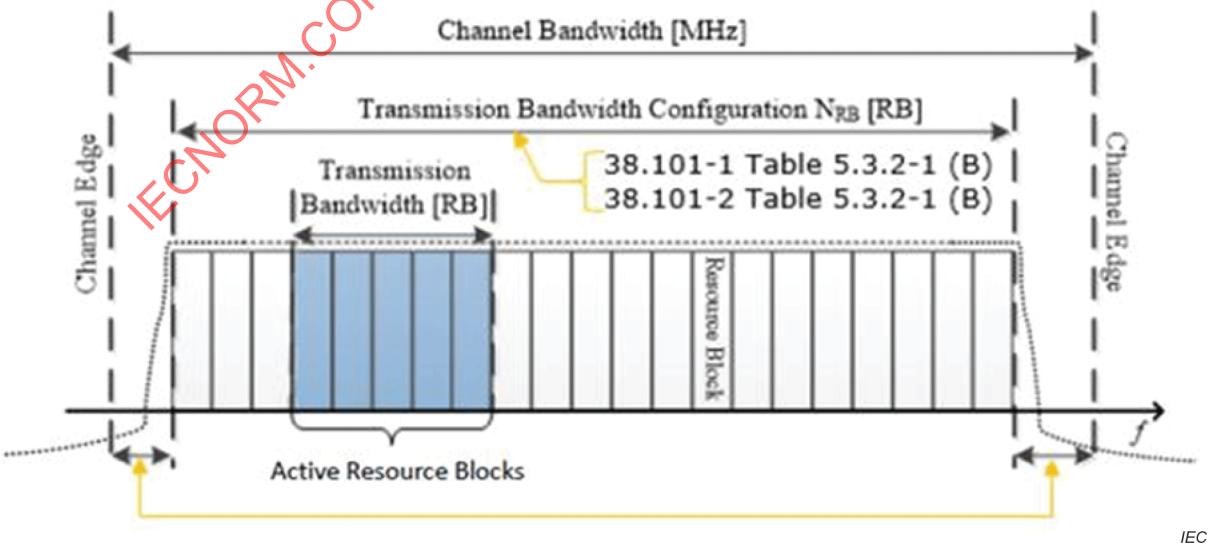


Figure E.21 – Representation of the channel bandwidth (CBW)

E.8.2.1.4 Method for beamforming antennas

If the radiation pattern of the SSB is different from that of other signals transmitted by the EUT (e.g. traffic channels), the extrapolation factor shall take into account the possible difference in the antenna gain, such that maximum possible RF field strength is obtained. The maximum electric field strength (V m^{-1}), E_{asmt}, is determined using Equation (E.17).

$$E_{\text{asmt}} = E_{\text{SSB}} \cdot \sqrt{F_{\text{extBeam}} \cdot F_{\text{BW}} \cdot F_{\text{PR}} \cdot F_{\text{TDC}} \cdot F_{\text{B}}^{-1}} \quad \text{(E.17)}$$

where

E_{asmt} is the extrapolation E-field strength (V m^{-1});

E_{SSB} is the measured E-field strength (V m^{-1}) per resource element (RE) of the strongest measured SSB beam (corresponds to $E_{\text{broadcast}}$ in Equation (B.59));

F_{extBeam} is the extrapolation factor corresponding to the ratio of the traffic radiation pattern envelope to the broadcast radiation pattern envelope at the direction to the evaluation location, see B.8.5;

F_{TDC} is the technology duty-cycle;

F_{PR} is the power reduction if the actual maximum approach is used, otherwise it is set to 1;

F_{B} is the ratio of the power transmitted for the SSB symbol to the traffic symbol (boosting factor). F_{B} is set to 1 if the power for the SSB and traffic symbols is the same or if the difference in power is already factored in F_{extBeam}.

F_{BW} is the ratio of the total carrier bandwidth to the subcarrier frequency spacing of the SSB.

The following SA configuration parameter recommendations apply when the EUT beam pattern is not available:

a) The centre frequency of the spectrum analyser should be set within the operating bandwidth of the EUT.

b) The frequency span should be set to zero (scope mode) in order to measure the received time signal for the traffic signals.

c) The resolution bandwidth (RBW) should be set smaller than the channel bandwidth (e.g. 1 MHz or lower).

d) The detector should be set to root mean square (RMS) mode; if the detector cannot be set to "RMS" mode, it can be set to "sample" or "peak" mode.

   1) When using "sample" or "peak" detector mode, a VBW smaller than the RBW should be used to avoid overestimation due to signal fluctuation. On the other hand, the VBW should be widened so that the transient time of the video filter is shorter than the duration of the target signal (PBCH, P-SS and S-SS) to avoid underestimation. If the time constant of the video filter is T_{video} (T_{video} = 1/(2π·VBW)), the transient time to obtain 95 % of the voltage is 3 × T_{video}. Therefore, in order to reduce the uncertainty while avoiding underestimation, VBW should be the smallest value with a transient time (3 × T_{video}) smaller than the duration of the measured signal (SSB). VBW examples are provided in Figure E.15, 10 kHz for NR FR1 with SCS of 30 kHz using a RBW of 1 MHz and 30 kHz for NR FR2 with SCS of 120 kHz using a RBW of 1MHz. The exact settings can be adjusted depending on the SA type, see Figure C.3.

   2) When using "RMS" detector mode, the VBW should either be equal to or higher than the RBW or switched off to avoid underestimation.

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e) The sweep time is set equal to approximately the product of the number of display points of the SA and the symbol duration in order to obtain an integration time close to the symbol duration of each pixel on the screen of the SA.

f) The maximum RF field strength per symbol among all samples collected over the measurement interval is selected (e.g. using the peak-hold function). Alternatively, the largest RF field strength value among the local maxima in the distribution of the RF field strength samples is retained (to filter out possible variations due to fading [125]).

g) Apply a factor of $\sqrt{\mathrm{SCS}/\mathrm{RBW}}$ to the measured field value in order obtain the RF field strength per RE.

h) F_{extBeam} is given by the squared valued of the ratio between the RF field strength value measured in this way and E_{SSB}.

This method assumes that, within the measurement time, the EUT is transmitting with the beam configuration leading to the maximum exposure value for the considered evaluation point. Since the RBW is chosen much smaller than the overall channel bandwidth, this condition can be met during normal traffic condition. Alternatively, traffic can be stimulated by positioning a UE in the same direction as the evaluation location similarly to what is described in B.4.2.5.4, see also [125]. When F_{extBeam} is estimated by means of in-situ measurements, it already includes possible differences in the power transmitted for broadcast and traffic symbols (i.e. F_{B} = 1). This is equivalent to extrapolate RF exposure directly from vector or scalar measurements of the PDSCH, as described in [126].

E.8.2.2 NR exposure extrapolation based on CSI-RS

E.8.2.2.1 Domain of application

This method is provided for information because it requires that a special mode is enabled in the NR BS in order to set a constant gain difference between traffic radiation pattern envelope and CSI-RS beam. Therefore, it is not always applicable.

NOTE The detailed specification of the above special mode is beyond the scope of this document.

Other specific modes can allow for the measurements of maximum exposure without the need for extrapolation (e.g. by forcing transmission at maximum power in specific direction).

E.8.2.2.2 CSI-RS configuration of the BS

The CSI-RS based method is applicable for extrapolation because the locations of the NR channel state information reference signals (CSI-RS) can be configured to be uniformly distributed over the occupied radio bandwidth to reduce effects of frequency selective fading. Multiple CSI-RS resources can be configured in the BS according to 3GPP. Therefore, the NR BS can add a CSI-RS configuration dedicated RF exposure measurement and extrapolation. The following CSI-RS configuration recommendations apply.

a) The time domain behaviour of CSI is periodic with a configurable repetition periodicity as described in 7.4.1.5.3 of 3GPP TS 38.211. For a CSI-RS resource configured as periodic or semi-persistent by the higher-layer parameter such as "resourceType" or configured by the higher-layer parameter such as "CSI-RS-CellMobility", the periodicity and offset should be obtained from the higher-layer parameter such as "CSI-ResourcePeriodicityAndOffset".

b) The port number of the CSI-RS should be equal to one port to reduce the overhead. The number of ports is given by the higher-layer parameter nrofPorts.

c) The density of the CSI-RS is configurable as described in 7.4.1.5.3 of 3GPP TS 38.211. The density is given by the higher-layer parameter density such as "CSI-RS-ResourceMapping IE" or the "CSI-RS-CellMobility IE".

d) The CSI-RS beam should be designed with a constant gain difference compared with traffic beam as shown in Figure E.22. Any remaining variability of F_{extBeam} in azimuth and elevation as defined in B.8.5 should be included in the uncertainty assessment.

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NOTE 1 Time domain and frequency domain resource allocation for the CSI-RS is flexible as specified in 3GPP. CSI-RS is configured by the RRC signalling. Therefore, CSI-RS transmission can be deactivated through RRC commands and the CSI-RS power can be measured if the signals are configured.

NOTE 2 The CSI-RS pattern, which has the constant gain different from the traffic beam, is a special configuration and needs to be activated by the BS as a special mode.

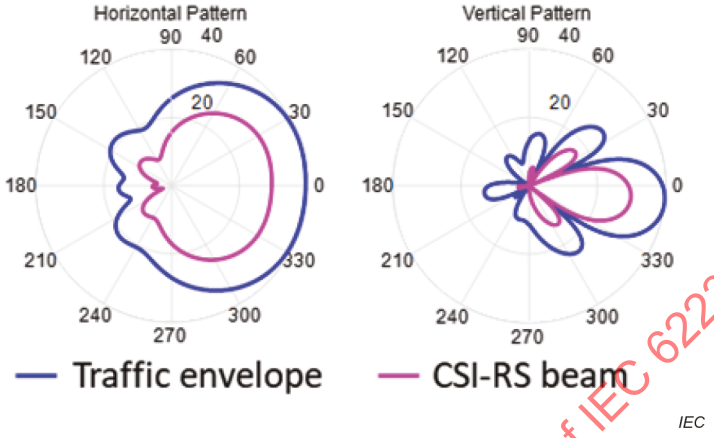


Figure E.22 – An example for one port CSI-RS beam design

E.8.2.2.3 Measurement method using a dedicated decoder

In this method, the RF field strength of the exposure measurement dedicated CSI-RS is measured. This type of measurement requires dedicated NR decoders or NR analysers.

a) The measurements require that the system bandwidth and centre frequency of the target NR carrier are set.

b) Identify the NR exposure measurement dedicated CSI-RS resource element (RE) location in both time and frequency domain (including the density, repetition periodicity), via known information from the network operator, or a NR decoder.

c) Measure the RF field strength of the NR BS exposure measurement dedicated CSI-RS resource element (RE), via a NR decoder.

d) Because the dedicated CSI-RS beam has constant gain difference with traffic beam, it is easy to extrapolate the RF field strength of the CSI-RS RE to the configured maximum RF field strength of the whole bandwidth of the NR BS.

For extrapolation, the maximum electric field strength (V m^{-1}), E_{asmt}, is defined by Equation (E.18).

$$E_{\text{asmt}} = E_{\text{CSI-RS}} \cdot \sqrt{F_{\text{extBeam}} \cdot F_{\text{BW}} \cdot F_{\text{PR}} \cdot F_{\text{TDC}}} \quad \text{(E.18)}$$

where

$E_{\text{CSI-RS}}$ is the measured field level (V m^{-1}) of CSI-RS per RE;

F_{TDC} is the technology duty-cycle;

F_{PR} is the power reduction if the actual maximum approach is used, otherwise it is set to 1;

F_{BW} is the total number of subcarriers within the carrier bandwidth;

F_{extBeam} is determined from the radiation pattern envelopes of the EUT as described in B.8.5.

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NOTE There is no parameter F_B in Equation (E.18) since boosting is generally not applied to CSI-RS.

E.9 Establishing compliance boundaries using numerical simulations of MIMO array antennas emitting correlated waveforms

E.9.1 General

To enhance system performance and service capabilities, multiple input multiple output (MIMO) transmission schemes, employed together with multiple antennas at the transmitter and receiver, are used. When assessing exposure from multiple electromagnetic sources the different contributions have to be combined. In this context, it is important to first determine whether the fields at the evaluation point should be regarded as correlated or uncorrelated.

The compliance boundaries of MIMO array antennas with densely packed columns emitting correlated waveforms, see Figure 7, can be evaluated using calculation methods and the requirements defined in 6.1. Both the case when all excited ports correspond to the same nominal polarization (denoted Co-pol case) and the case when the excited ports correspond to orthogonal nominal polarizations (denoted X-pol case) are considered.

Complementary information on the technical background can be found in [34], [119], [127], [128], [129].

E.9.2 Field combining near base stations for correlated exposure with the purpose of establishing compliance boundaries

Accurate field combination of correlated fields involves a vector-summation of the individual field components which need to be known to both amplitude and phase.

For array antennas it is well known that beams are formed by changing the excitation coefficients. The resulting increase of the received power is used to enhance the performance of the communication channel. Beamforming can either be performed by selecting the excitation vector from a set of pre-defined vectors, also known as codebook-based beamforming, or by applying an arbitrary excitation at the transmitter side.

Usually, the RF exposure is to be time-averaged over several minutes before being compared with applicable exposure limits. Depending on the traffic and radio conditions, the excitation coefficients vary in most cases over a much shorter time frame, which makes a straightforward application of the true vector sum impractical to work with. Instead, a conservative approach can be adopted where the exposure is maximized for every evaluation point in accordance with the field combining method considered. Even though this resulting field distribution in the vicinity of the antenna is not physically realizable for any single array excitation, the approach is justified by the objective to determine a conservative compliance boundary. The approach has the advantage that knowledge of the exact excitations is not needed; simplifying the exposure evaluation.

For the case where the amplitude distribution of the excitation is fixed and known but the phase is varying arbitrarily, a conservative approach based on the summation of RF field strength magnitudes was presented in [41]. Using this method, the combined electric field strength can be written using Equation (E.19).

$$E_{\mathrm{RMS}}(r) \le \sum_{n=1}^{N} \left| w_n \cdot \left| E_n(r) \right| \mathrm{RMS}' \right| \quad \text{(magnitude method)} \tag{E.19}$$

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where w_n denotes the complex excitation coefficients associated with port n and N denotes the total number of ports. In the following this method is referred to as the magnitude method. For the case where the excitations vary in both amplitude and phase for a fixed transmitted power, it is possible to analytically determine an optimal set of weight coefficients per evaluation point which is maximizing the combined RF field strength. The combined electric field strength can then be obtained using Equation (E.20).

$$E_{\mathrm{RMS}}(r) = \left| \sum_{n=1}^{N} w_n^{\mathrm{opt}} \cdot E_n(r) \right|_{\mathrm{RMS}'} \quad \text{(optimal weights method)} \tag{E.20}$$

where the optimal set of weights $w^{\mathrm{opt}} = \left(w_1^{\mathrm{opt}}, \ldots, w_N^{\mathrm{opt}}\right)$ is to be determined as the eigenvector corresponding to the largest eigenvalue of the $N \times N$ matrix P with elements using Equation (E.21):

$$P_{mn}(r) = E_m^*(r) \cdot E_n^*(r) \text{ for } m = 1 \ldots N, \text{ and } n = 1 \ldots N \tag{E.21}$$

In the following, this approach is denoted as the optimal weights method.

A comparison between field combining methods for realistic MIMO BS antennas is provided in [130].

E.9.3 Numerical simulations of MIMO array antennas with densely packed columns

For the considered antenna type, the distance between the array columns can be quite small, typically around 0,5 wavelength. As a consequence, effects of mutual coupling between the antenna elements in the numerical simulations should be considered. At the same time, it is desirable to obtain field distributions for each port separately to be able to apply the field combination methods outlined above. To satisfy both these requirements an embedded pattern approach can be used where each port is excited and simulated separately with the other ports terminated in matched loads. In situations where both the amplitude and the phase of the excitation vary, the optimal weights method can be used to provide an upper bound of the combined RF field strengths levels for both co-polarization (Co-pol) and cross-polarization (X-pol) configurations.

For situations where the excitation amplitudes are fixed but the phases are varying, different approaches are applicable for Co-pol and X-pol configurations. For Co-pol configurations, a straightforward application of the conservative magnitude method has been found to produce only a minor overestimation of the compliance boundary dimensions compared with a best estimate method. Alternatively, a semidefinite relaxation approach [131] can be applied to (E.21) to compute the upper bound of the maximum combined RF field strength. This approach gives less overestimation, but more sophisticated computation compared with the magnitude method. A similar application of the magnitude method for the X-pol case leads to a significant overestimation of the front compliance distance. The reason is that fields associated with ports of different antenna polarization are essentially uncorrelated in this direction. Instead, the following approach can be used, which has been found to produce conservative and accurate results compared with a best estimate method.

a) Columns/ports corresponding to one of the nominal polarizations (e.g. +45°) are simulated and the corresponding RF field strengths in the vicinity of the BS antenna are calculated.

b) The power per port, compared with the case when all ports are excited, is doubled. Here it is assumed that the number of +45° ports equal the number of −45° ports.

c) The fields are combined using the magnitude method.

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E.9.4 Numerical simulations of large MIMO array antennas

For an array antenna with N ports, the approach described in E.9.3 implies that RF field strength results from N separate embedded element simulations are required. For large antenna arrays, this procedure becomes very costly in terms of computational resources.

In large array antennas, many of the elements are surrounded by other elements and therefore sense a similar electromagnetic environment. For these antenna arrays an approximate approach can be used whereby the total transmitted field is constructed by summing the spatially shifted field distribution of a centrally located element [132]. To better consider effects of the edge and corner elements, the centre element solution can be replaced by the corresponding field distributions for an edge and a corner element for elements located on the outer rim of the array.

In [132], it was found that for arrays with 5 × 5 elements or more, the approximate solution based on the spatially shifted field distribution of a centrally located element resulted in a relative error magnitude in terms of front compliance distance of less than 5 %. The improvement in evaluation time, compared with the rigorous embedded element simulation approach described in E.9.3, is proportional to the number of ports in the array.

If coupling between radiating elements can be neglected, the synthetic model from B.7.1 can be used to determine the RF field strength of large MIMO array antennas and is not costly in terms of computational resources

E.10 Massive MIMO antennas

E.10.1 Overview

Massive MIMO antenna systems can be deployed in telecommunications (e.g. TD-SCDMA) networks to reduce interference. Massive MIMO antennas produce a number of simultaneous narrow beamwidths directed to individual users to optimize communications. The power fed to the antenna is therefore split between users and the instantaneous directivity adjusted, i.e. massive MIMO antennas have different directivity for each individual communications channel. Therefore, if the RF field strength is evaluated in one fixed position near the BS, the measured value is significantly varying from time to time.

For a compliance evaluation, the requirement is to define the set of conservative BS parameters for a BS under normal use, i.e. non-fault conditions. This requires a detailed analysis specific to the employed technology and with due consideration for any site-specific factors.

E.10.2 Deterministic conservative approach

The gain per user is generally several decibels higher than the equivalent average gain over all channels. A very conservative case can be derived from the maximum gain in any direction and the total radiated power. This would be equivalent to having all communications channels operating at maximum power and all the individual directed beams aligned towards the evaluation point. This is an unrealistic case; nevertheless, it is simple to apply.

E.10.3 Statistical conservative approach

a) In developing a robust statistical model, at least the following aspects should be considered.

   1) Antenna design: What is the narrow beam pattern? When swept over full range of directions, what is the overall configured envelope radiation pattern?

   2) Antenna steering: Is the narrow beam continuously steered or is it selected from a (few) fixed orientations? Is the narrow beam adjusted in φ alone or in both θ and φ.

   3) Technical limitation: Are there any design constraints that limit the fraction of available power directed to a single narrow beamwidth? What fraction of the available power can be directed to a single user?

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4) Geographic distribution of users in relation to antenna: Are there any factors that slue the geographic distribution of users from "random"? For example, if a BS is located 1 000 m from a conference centre within the coverage area of the cell, it can be anticipated that there is a significant concentration of users over a limited range of bearings.
5) RF field strength modelling: Select a suitable computation model from Clause B.3 or Clause B.6 and respect any constraints on applicability, see Table B.16. Consider that when approaching closer to an antenna with very narrow beamwidth, a person can obstruct more than one beam.

b) In general, a statistical model defines:
1) the computation or measurement methods from Clause 8 to either establish the conservative RF field strength / SAR / power density or a reference (e.g. "average") RF field strength / SAR / power density;
2) a function defining a factor to reduce the deterministic conservative case or to modify the reference RF field strength / SAR;
3) the applicability constraints considering all relevant aspects and at least a) to d) above and any assumptions that apply;
4) the level of conservativeness and allows for that level to be parametrically expressed in the corresponding analytical formulation.

In the case study associated with the example approach, see E.10.4, the computed deterministic conservative power density is 0,5 W m^{-2} and the statistical conservative power density is 0,23 W m^{-2} for a level of conservativeness of 97,6 %.

E.10.4 Example approaches

E.10.4.1 General

Figure E.23 presents a plan view of a massive MIMO antenna with N_u independently steerable (in φ only) narrow beams each of beamwidth NB_{3dB} combining to provide coverage over a cell sector beamwidth of $SMRT_{3dB}$. Each beam is directed to a single user within the coverage area. The example approaches evaluate the RF field strength at the evaluation point in accordance with deterministic conservative, long term time-average and statistical conservative methods.

The following definitions are used, see Figure E.23:

G_u is the maximum gain of the narrow beam directed to a user;

$D_{\varphi side}$ is the maximum horizontal directivity of the side lobes of the narrow beam;

$D_{\theta ep}$ is the vertical directivity of the narrow beam directed to the evaluation point;

$SMRT_{3dB}$ is the −3 dB horizontal beamwidth (°) of the configured envelope radiation pattern of the massive MIMO antenna;

NB_{3dB} is the −3 dB horizontal beamwidth (°) of the narrow beam directed to each user;

φ_{ep} is the bearing (° East of North) to the evaluation point;

φ_{mMIMO} is the boresight bearing (° East of North) of the massive MIMO antenna if $SMRT_{3dB} < 360°$;

P_u is the maximum value of the average (temporal) transmitted power (W) for each user;

N_u is the maximum number of simultaneous users;

P_{avg} is the maximum value of the average (temporal) transmitted power (W) for the massive MIMO antenna and $P_{avg} = P_u \cdot N_u$;

NOTE 1 In the case where a different transmitted power level is available to each user, the definition of P_u implies that $P_{avg} \leq P_u \cdot N_u$, ensuring the conservativeness of the computed power density.

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N_{max} is the statistically defined maximum number of users in a single narrow beamwidth φ_{3dBu} (see Figure E.23 "MAX") centred on the evaluation point bearing φ_{ep}, i.e. within bearing range $\varphi_{ep} - \frac{NB_{3dB}}{2} \le \varphi \le \varphi_{ep} + \frac{NB_{3dB}}{2}$;

N_{adj} is the statistically defined (considering N_{max}) maximum number of users in the two bearing ranges (see Figure E.23 "ADJACENT") $\varphi_{ep} - \frac{3 \times NB_{3dB}}{2} \le \varphi \le \varphi_{ep} - \frac{NB_{3dB}}{2}$ and $\frac{NB_{3dB}}{2} \le \varphi \le \varphi_{ep} + \frac{3 \times NB_{3dB}}{2}$;

N_{oth} is the number of remaining users (after considering the statistically defined N_{max} and N_{adj}) in bearing ranges (see Figure E.23 "OTHER") $\varphi_{ep} - \frac{SMRT_{3dB}}{2} \le \varphi \le \varphi_{ep} - \frac{3 \times NB_{3dB}}{2}$ and $\frac{NB_{3dB}}{2} \le \varphi \le \varphi_{ep} + \frac{3 \times SMRT_{3dB}}{2}$;

δ_{max} is the factor modifying the effective gain in the direction of the evaluation point of the set of narrow beams serving users in a "MAX" bearing range centred on φ_{ep} (see Figure E.23) considering the distribution of users (see N_{max}) within the bearing range;

δ_{adj} is the factor modifying the effective gain in the direction of the evaluation point of the set of narrow beams serving users in the two "ADJACENT" bearing ranges (see Figure E.23) considering the distribution of users (see N_{adj}) within the bearing ranges;

δ_{oth} is the factor modifying the effective gain in the direction of the evaluation point of the remaining set of narrow beams serving users in the two "OTHER" bearing ranges (see Figure E.23) considering the distribution of users (see N_{oth}) within the bearing ranges.

Assume that the RF fields transmitted to each user are non-correlated and can be summed to find the total power density, see IEC TR 62630 [41].

NOTE 2 The validity of this assumption is technology dependent.

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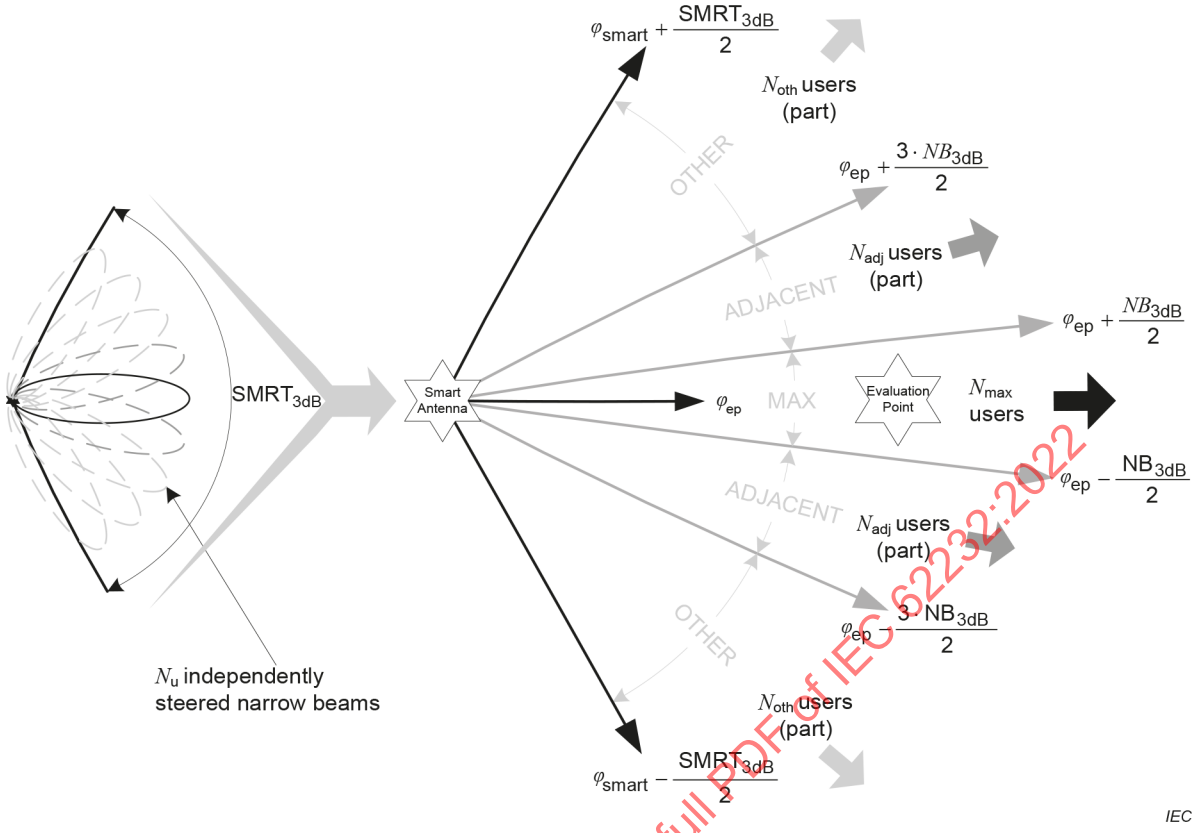


Figure E.23 – Plan view representation of statistical conservative model

E.10.4.2 Deterministic conservative power density model

Considering Figure E.23, this model assumes that all N_u users are in the same direction as the evaluation point and that all the transmitted power is directed towards the evaluation point, i.e. $N_{max} = N_u$. The deterministic conservative power density can be determined using the evaluation methods in this document in accordance with their validity. However, as an example, Equation (E.22) uses the simple spherical formula, see Equation (B.1).

$$S_{det} = \frac{P_{avg} \cdot G_u \cdot D_{\theta ep}}{4\pi \cdot r^2} \quad \text{(E.22)}$$

NOTE Where a single reflector is present, a factor of $(1 + |\Gamma|)^2$ is appropriate using the classical spherical formula, see Equation (B.7).

E.10.4.3 Long term time-average power density model

Considering that over a long time period each narrow beam is effectively covering the full massive MIMO antenna beam width, the effective gain of each of the narrow beams is therefore reduced by the ratio of these two beam widths such that the long-term (e.g. over several days) time-averaged power density S_{avg} can be expressed by Equation (E.23).

$$S_{avg} = S_{det} \cdot \frac{NB_{3dB}}{SMRT_{3dB}} \quad \text{(E.23)}$$

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This value is significant only in that it establishes a possible basis for estimating the long term overall environmental RF exposure level from the BS.

E.10.4.4 Statistical conservative power density model

E.10.4.4.1 Overview

A statistical approach can be used to define a more realistic conservative power density value. This is based on defining a very small but acceptable probability that, over the (limited) time that the cell is fully loaded, the statistical conservative value can be exceeded.

NOTE For example, consider the case where a) the fully loaded situation (maximum power to all users on cell edge, all frequencies/timeslots in use, maximum data rate, etc.) occurs for say 5 % of the time and b) the defined acceptable probability for exceedance is 2,5 %. The probability that the computed value is exceeded is 2,5/100 × 5/100 = 12,5/10 000 or 0,125 %. This means that over time, there is 99,875 % probability that the real value is below the statistically conservative value compared with 100 % probability for the deterministic conservative approach.

In the statistical conservative case, it is still necessary to account for all the transmitted power, but not necessarily with all the users in a single narrow beamwidth as in the deterministic conservative case.

The example approach breaks the problem into three parts.

a) To establish the deterministic conservative power density (S_u) from a single narrow beam supporting one user considering the maximum gain modified by the vertical directivity to the evaluation point.
b) To establish appropriate factor(s) (δ_{max}, δ_{adj}, δ_{oth}) to modify the horizontal gain of the narrow beams considering that some of the transmitted power is targeted at users at bearings other than the evaluation point.
c) To establish a statistical model defining the number of users (N_{max}, N_{adj}, N_{oth}) in appropriate bearing ranges considering the field computation model constraints and the level of conservativeness. This effectively defines the transmitted power distribution over the massive MIMO antenna beamwidth.

The statistical conservative power density S_{sta} is defined by Equation (E.24).

$$S_{sta} = S_u \cdot \left(N_{max} \cdot \delta_{max} + N_{adj} \cdot \delta_{adj} + N_{oth} \cdot \delta_{oth} \right) \quad \text{(E.24)}$$

In Equation (E.24), the subscripts relate to the "MAX", "ADJACENT" and "OTHER" bearing ranges shown in Figure E.23.

E.10.4.4.2 Establishing the single user conservative power density

In principle, any of the evaluation methods described in Clause 8 can be applied to determine S_u depending on the criteria in Clause 7 and Annex A and due consideration of their applicability to source-environment plane regions within which the evaluation point(s) lie. For simplicity, the simple spherical method, see B.3.1, is used with the horizontal gain at maximum and the vertical directivity appropriate for the evaluation point. For a single user, for evaluation points in the source-environment plane region III-0, the conservative power density S_u can be expressed by Equation (E.25).

$$S_u = \frac{P_u \cdot G_u \cdot D_{\theta ep}}{4\pi \cdot r^2} \quad \text{(E.25)}$$

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