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TECHNICAL REPORT

Dynamic modules –
Part 6-7: Design guide – Optical channel monitor

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FOREWORD

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IEC 62343-6-7, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/1252/DTR	86C/1274B/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of IEC 62343 series, published under the general title *Dynamic modules,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

DYNAMIC MODULES –

Part 6-7: Design guide – Optical channel monitor

1 Scope

This part of IEC 62343, which is a technical report, describes optical channel monitor modules, one of several important classes of dynamic modules that are used in dynamic optical networks. This report includes a description of the necessity of optical channel monitors, specifically in the context of dynamic optical networks, and how this is driving feature and performance requirements. This technical report surveys the different categories of optical channel monitor technologies that are being used and highlights some of their unique characteristics. Also described are different possible approaches for characterizing and specifying the performance of optical channel monitor modules.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 62343, *Dynamic modules – General and guidance*

ITU-T Recommendation G.697, *Optical monitoring for dense wavelength division multiplexing systems*

3 Terms, definitions and abbreviations

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 62343 apply.

3.2 Abbreviations

Abbreviation	Term
ASE	amplified spontaneous emission
DWDM	dense wavelength division multiplexing
InGaAs	indium gallium arsenide
LOS	loss of signal
NIR	near infrared
OSNR	optical signal-to-noise ratio
PDL	polarization dependent loss
ROADM	reconfigurable optical add/drop multiplexers
SOP	state of polarization

4 Existing standards

ITU-T Recommendation G.697 was initially approved in June 2004 by ITU-T Study Group 15 (2001-2004). This recommendation and its subsequent revisions cover a broad scope of optical monitoring methods, including time domain methods, frequency domain methods, indirect methods, embedded methods and external methods. The recommendation reviews the full scope of optical impairments in DWDM transmission systems, and it prioritizes these impairments by relative probability of occurrence, thus prioritizing the monitoring features for the channel monitor. The recommendation describes the optical impairments of high relative frequency of occurrence to be:

- attenuation of transmission paths;
- optical channel power changes due to gain variations;
- frequency (or wavelength) deviation from nominal.

ITU-T Recommendation G.697 also proposes, but does not require, specifications relating specifically to embedded optical monitoring, including:

- performance of embedded optical monitoring at the DWDM receiver input;
- performance of embedded optical monitoring without OSNR;
- performance of embedded optical monitoring with OSNR.

ITU-T Recommendation G.697 also dedicates a significant section to interpolated OSNR measurements and the difficulty of such interpolated OSNR measurements in certain network architectures. ITU-T Recommendation G.697 refers to IEC 61280-2-9[1][1] as a useful reference for additional information on OSNR measurements.

It may be useful to point out that ITU-T Recommendation G.697 was drafted in 2004 in the context of point-to-point DWDM transmission networks, just before general adoption of reconfigurable optical add/drop multiplexers (ROADM) in the network around 2005. The ROADM has since become the core element of a new generation of optical systems that have been characterized as dynamic and for which dynamic modules are required. These dynamic optical systems embody the limitations in OSNR measurements that were already anticipated in ITU-T Recommendation G.697. Recently, dynamic optical networks have expanded the role and requirements for optical channel monitor modules due to the nature of their dynamic capabilities.

5 The role of optical channel monitors in dynamic optical networks

5.1 General

Dynamic optical networks exhibit the following characteristics:

- The capability to express optical signals of a given wavelength through optical networking nodes in the optical domain, thus bypassing the conversion to the electrical domain;
- The capability to switch optical signals of a given wavelength between a set of ingress and egress optical ports;
- The capability to manage the optical channel attributes, including channel power, as the channels are configured to traverse particular paths through the network;
- The capability to support a large number of interconnected optical rings or a multi-wavelength mesh topology.

The optical channel monitor function assists with each of these capabilities as described below.

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1 Numbers in square brackets refer to the Bibliography.

5.2 Signal performance monitoring and fault isolation

The capability to express optical signals of a given wavelength through nodes in the optical domain allows optical signals to bypass the conversion to the electrical domain. When suitable for the application, this provides a savings in cost. However, any signal performance monitoring and fault isolation capabilities that reside in the electrical domain are no longer available to the network management system. This is mitigated by monitoring the signal performance in the optical domain. The optical channel monitor performs that function. In a broader sense, devices that are categorized as optical performance monitors also perform that function using more sophisticated measurements. Table 1 compares the general features of the optical channel monitor and the optical performance monitor.

Table 1 – High level comparison of optical channel monitor and optical performance monitor features

Features	Optical channel monitor	Optical performance monitor
Channel identification	Required	Required
Channel power	Required	Required
Channel frequency	Optional	Optional
Optical signal-to-noise ratio	Optional	Required
Chromatic dispersion	Not applicable	Optional
Polarization mode dispersion	Not applicable	Optional

Table 1 indicates that the optical performance monitor distinguishes itself from the optical channel monitor with advanced features. This typically requires a device architecture that does not fall within any of the three broad optical channel monitor architectures shown in Figure 2. As a result, the optical performance monitor is beyond the scope of this technical report. References to optical performance monitor technologies and measurement methods can be found in the bibliography, including IEC 61280-2-9 and IEC 61280-2-11 [2]. For a comprehensive treatment of advanced optical performance monitor techniques, please refer to the text by Calvin C.K. Chan (Academic Press) [3] which includes the following topics:

- optical performance monitoring
  - based on optical sampling;
  - based on pilot tones;
  - based on electronic digital signal processing;
  - based on nonlinear optical techniques;
  - of optical phase modulated signals;
  - for coherent optical systems;
  - chromatic dispersion monitoring;
  - polarization mode dispersion monitoring.

5.3 Channel inventory and routing management

This is the capability to switch optical signals of a given wavelength between a set of ingress and egress optical ports. It drives the simple requirement for independent verification so that wavelengths are properly routed to the intended ports. The optical channel monitor performs that function.

5.4 Dynamic channel power self-management

The capability to support a large number of interconnected optical rings or a multi-wavelength mesh topology drives the requirement for self-managed optical networks. A common attribute of this architecture is the need for optical nodes to return to a known state at the egress optical port. In practice, this requirement is often met by equalizing the DWDM channels around a desired per-channel optical launch power. The actuators that vary the attenuation of each individual DWDM channel are found in dynamic gain equalizers or within wavelength selective switches. Optical channel monitor modules are used to close the control loop.

6 Review of optical channel monitor technologies

6.1 General

A common feature of all optical channel monitor modules is that they operate off of a fraction of the optical transmission signal. To achieve this, they are typically connected to a 1 % to 5 % passive optical tap coupler as shown in Figure 1.

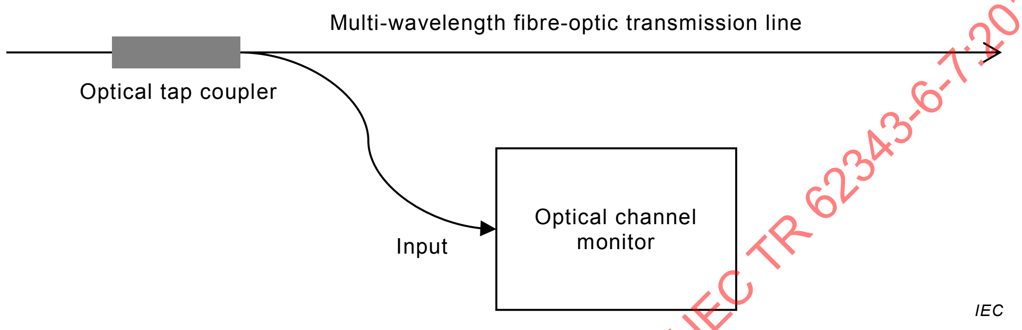
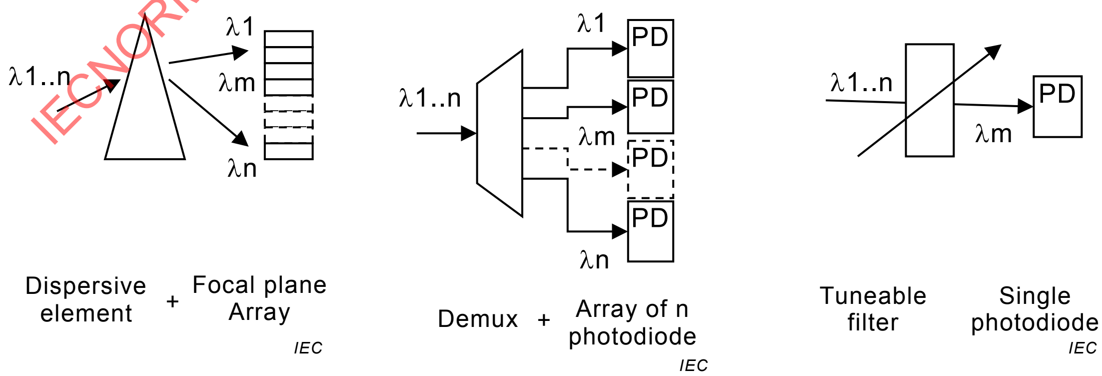


Figure 1 – Fraction of the optical power in the multi-wavelength transmission line tapped and fed to the input of an optical channel monitor for spectral analysis

There are many technologies that can be used to construct an optical channel monitor that reports the optical power and wavelength of each optical channel. Each technology can be categorized within three broad categories that could be described as:

- spatial wavelength dispersion and focal plane array detection,
- dedicated photodiode per demultiplexed wavelength,
- tuneable filter and single photodiode element.

Each of these technology categories are determined by their commonality in the optics function as well as the photo-detection architectures, as shown in Figure 2. These three technology categories are described below in more detail. For each of these technology categories, the optics and the photo-detection architectures are discussed separately.



a) – Spatial wavelength dispersion and focal plane array detection

b) – Dedicated photo- diode per demultiplexed wavelength

c) – Tuneable filter and single photodiode element

Figure 2 – Optical channel monitors – Three broad architecture categories

In addition, the overall performance of an optical channel monitor is a combination of hardware and software capabilities. The hardware performance is fundamentally defined by the optical and photo-detection design. The software can enhance the optical channel monitor performance with signal processing algorithms. However, the ability to implement signal post-processing algorithms in the first place is determined by the hardware architecture itself. For this reason, it is also useful to discuss not only optical and photo-detection designs but also the potential for signal post-processing in the context of each technology category.

6.2 Spatial wavelength dispersion and focal plane array detection

6.2.1 General

Optical channel monitor modules that use spatial wavelength dispersion technologies have perhaps the longest track record, as they were deployed in the early DWDM transmission systems. These channel monitor technologies are largely an adaptation of near infrared (NIR) spectrometer designs that were available at the time of the advent of DWDM transmission technology.

6.2.2 Spatial wavelength dispersion technologies

Several spatial wavelength dispersion technologies have been used, including:

- blazed-fibre Bragg gratings;
- diffraction gratings;
- volume phase gratings;
- silica-based planar lightwave circuits.

One commonality of all the above technologies is that the DWDM signal is dispersed in a single spatial dimension designed to be compatible with one-dimensional focal-plane array geometry where the optical signal is detected. The optics are designed such that the channel plan is translated spatially over the length of the focal plane array. The wavelength resolving performance of each optical technology listed above, combined with the pixel density of the focal plane array determines the hardware contribution to the overall optical performance of the optical channel monitor.

6.2.3 One-dimensional focal plane arrays

This category of optical channel monitor modules is characterized by the use of one-dimensional focal plane arrays. These focal plane arrays typically consist of 256 or 512 or more rectangular-shaped photodiodes (pixels) laid-out side-by-side, for example on a pitch of the order of 25 µm. A photodiode array is combined with one or two electronic multiplexers. If two electronic multiplexers are used, they are typically placed on each side of the photodiode array. One electronic multiplexer is connected to the odd-numbered pixels while the other electronic multiplexer is connected to the even-numbered pixels. The role of the electronic multiplexer is to integrate the current of each individual pixel over a finite amount of time and store it in a capacitor. At the end of the integration time, each capacitor is read out as voltage sequentially. The result is a “boxcar” voltage signal on the output of the electrical multiplexer that represents the serial output of the integrated optical signal of each photodiode pixel.

6.2.4 Signal processing capabilities

The raw signal from the focal plane array represents a relatively high resolution spectral response of the optical system convolved with the input optical spectrum. It is therefore possible to apply peak detection and deconvolution algorithms to enhance the performance characteristics of these optical channel monitor modules and enable features such as channel identification vs. filtered ASE signals. The efficacy of enhanced processing algorithms generally improves with increasing pixel count. One relative disadvantage of this technology is that the photocurrent integration time and the algorithm processing time yield an overall response time that tends to be slow, which is usually not considered practical for protection switching detection, although fine for signal restoration.

6.3 Dedicated photodiode per demultiplexed wavelength

6.3.1 General

An optical channel monitor can also be designed by adding a photodiode at each port of a wavelength demultiplexer. Initial designs using wavelength demultiplexers based on thin-film filters were not as widely accepted as the later designs using wavelength demultiplexers based on planar lightwave circuits. These planar lightwave circuits proved to be more economical and smaller in size for large wavelength counts. Since planar lightwave circuits offer the promise of integrated functionality, a wide range of designs were proposed with various levels of integration.

6.3.2 Demultiplexer technologies

The following designs have been proposed:

- arrayed waveguides in silica on silicon;
- echelle grating waveguides in indium phosphide;
- bulk gratings.

6.3.3 Photodetector technologies

The photodetectors proposed for these applications are typically based on InGaAs technology. However, different levels of integration have been proposed including:

- discrete photodiodes in a coaxial package, each with a fibre pigtail;
- photodiode arrays packaged with a ribbon fibre pigtail;
- discrete photodiode chips flipped chipped on silicon substrate of a demultiplexer;
- photodiode array sliver bonded directly on silicon substrate of a demultiplexer;
- photodiodes monolithically integrated in indium phosphide substrate of a demultiplexer.

6.3.4 Signal processing capabilities

The signal output is a continuous parallel stream of photocurrent measurement of each photodiode corresponding to each wavelength measured. Therefore, the output signal does not lend itself to peak detection and deconvolution algorithms. Another disadvantage of this technology is the inability to address future flexible grid applications where the channel plan contains DWDM channels of varying bandwidth which are spaced on irregular frequency intervals on the ITU grid.

One attribute enabled by the continuous monitoring of each wavelength is the ability to detect low-frequency signals that systems can use to perform wavelength identification and tracking throughout the optical network. One relative advantage is that the overall response time can be significantly lower than 1 s, which can be practical for protection switching detection and signal restoration.

6.4 Tuneable filter and single photodiode element

6.4.1 General

The optical channel monitor designed with a tuneable filter and a single photodiode element comes in the widest variety of technology options.

6.4.2 Tuneable filter technologies

Tuneable filter technologies used in channel monitors include the following:

- cleaved-fiber Fabry-Perot cavity tuned by varying the physical cavity length;

- fibre-Bragg gratings tuned using compressive or tensile longitudinal stress;
- fibre-Bragg gratings tuned using acousto-optic actuation;
- MEMS Fabry-Perot filters tuned by varying the physical cavity length;
- MEMS mirrors combined with diffraction gratings;
- MEMS mirrors combined with volume phase gratings;
- piezo-based Fabry-Perot filters tuned by varying the physical cavity length;
- planar waveguide tuneable filters using thermo-optic actuation;
- thin-film tuneable filters using mechanical rotation;
- thin-film tuneable filters using acousto-optic actuation;
- thin-film tuneable filters using thermo-optic actuation.

6.4.3 Photodetector technology

The photodetector is typically made from widely available InGaAs technology. The photodiode can be integrated in the optical channel monitor module using a coaxial fibre-pigtailed package. Another option is to package the photodiode within the tuneable filter package.

6.4.4 Signal processing capabilities

The raw signal from the photodiode represents a continuous spectral response of the optical system convolved with the input optical spectra. It is therefore possible to apply peak detection and deconvolution algorithms to enhance the performance characteristics of these optical channel monitor modules and enable features such as channel identification vs. filtered ASE signals. The efficacy of enhanced processing algorithms is generally improved in tuneable filter devices because of the large number of spectral data samples. One relative disadvantage of this technology is that the filter tuning time and the algorithm processing time yield an overall response time that tends to be slow, which is usually not considered practical for protection switching detection, although fine for signal restoration.

7 Monitoring parameters

7.1 General

In the context of dynamic optical networks, the key monitoring parameters for optical channel monitor modules are described in the following subclauses.

7.2 Channel identification

Channel identification is a fundamental capability of the optical channel monitor to perform one or several of the following functions:

- correctly assign each detected channel to its corresponding ITU channel frequency in THz;
- identify genuine channels vs. amplified spontaneous emitted noise (ASE). This includes the ability to discriminate between 40 Gb/s signals (and above) from ASE filtered by wavelength cross-connect filters or interleavers;
- identify 10 Gb/s vs 40 Gb/s and 100 Gb/s signals in mixed bit-rate applications.

Channel identification is important to avoid false positives and false negatives which could raise high severity alarms in the optical network and trigger significant and costly remedial action. Channel identification is also important during channel turn up: as the power of the channel is turned up, the system should determine as early as possible if the channel is present.

Channel bit rate identification can be useful to determine if the measurement of channel power is best performed over a wider or narrower integration bandwidth. The topic of integration bandwidth is discussed in more detail below in the context of practical considerations in preparation for standardizing optical channel monitor specifications.

7.3 Channel power

Once a channel has been identified, it can be acted on mainly by increasing or decreasing the optical power. In dynamic optical networks, DWDM signals should be able to pass through (or express through) several nodes transparently, and DWDM signals can be added and dropped at any optical node. As a result, systems engineers typically design ROADM nodes to equalize the power of all the channels in the outgoing DWDM signal. The equalization is typically performed by the variable optical attenuator built into the optical switch.

When a new optical circuit is provisioned and a transmitter is turned up, the system should also be able to recognize the channel and progressively step up the optical power until it comes to parity with the other channels.

For both channel equalization and channel turn-up applications, relative channel power accuracy is a relevant parameter. Good relative channel power accuracy is where a low variation can be found in the absolute channel power accuracy from channel to channel across the channel plan. For both applications mentioned above, the relative power accuracy becomes more important as the channels come close to being equalized. The degree of spectrum flatness that can be achieved by the dynamic system depends on the relative channel power accuracy that the optical channel monitor can achieve.

7.4 Total power (composite power)

The total power is optional because of its limited practical usefulness. The total power provided by an optical channel monitor is typically the integral of all the optical power present at the input from half a channel before the first channel to half a channel after the last channel. As such, it is not exactly equivalent to the total power reported by a photodiode with a larger bandwidth. The total power reported by the channel monitor should be compared to a similar measurement performed by an OSA.

Total power measurements are also degraded in the presence of few channels at low power. In this case, the optical channel monitor may no longer be able to distinguish between the true ASE noise and the noise floor of the electronics. The noise floor of the electronics may be interpreted as ASE and incorrectly factored into the total optical power reported. For this reason, it is typically recommended to simply use the sum of all the channel powers rather than the total power to determine a loss of signal (LOS) condition.

7.5 Channel frequency

The channel frequency is optional because it is a parameter that can not as readily be acted upon or that is already separately managed at the transceiver where the signal is sourced.

7.6 Optical signal to noise ratio (OSNR)

OSNR is optional because of the well documented challenges of providing a relevant measurement in dynamic optical networks. One standard method known as the peak-to-valley method (or out-band OSNR) is typically recognized as not being applicable in the context of dynamic optical networks because of the ASE filtering that takes place between the channels as the signal moves through optical switching nodes. New and more sophisticated OSNR monitoring methods are called for. Collectively, they are generally referred to as in-band OSNR methods. These in-band OSNR methods are still maturing. They also require additional hardware which implies a trade-off in cost versus benefit that should be considered independently for each individual system design.

8 Practical considerations in preparation for standardizing optical channel monitor specifications

8.1 General

An optical channel monitor is fundamentally a measuring instrument for which the measurement capability becomes an intrinsic part of the overall dynamic system budget. Various dynamic systems account for optical channel monitor performance in different ways. The result can be widely differing optical channel monitor specifications to suit the needs of different dynamic system designs. The items discussed below should be considered carefully as the IEC moves towards the standardization of optical channel monitor specification templates.

8.2 All-inclusive vs. break-out approaches to the specification

8.2.1 General

The optical channel monitor performance should be considered over the range of several operating condition parameters. These operating condition parameters include:

- total number of channels and channel spacing on the ITU grid;
- input laser frequency tolerance around the ITU grid;
- input laser state of polarization (SOP);
- per-channel optical power dynamic range;
- adjacent and non-adjacent channel power uniformity (or non-uniformity);
- bit rate and modulation formats present for each channel;
- input OSNR range;
- operating temperature;
- operating humidity.

There are two approaches to defining the optical channel monitor specification. Depending on which approach is selected, the test methodology and therefore the specification template should be adapted accordingly.

8.2.2 All-inclusive approach to the optical channel monitor specification

One approach is to assign a worst-case performance budget for each performance parameter of the optical channel monitor that are all-inclusive of the entire set of operating conditions. The trade-off of this approach is that the corner cases will add up to force a more relaxed specification. Should the resulting optical channel monitor performance not fit in the overall system design budget, this may restrict the optical channel monitor technology selection to higher performance and typically higher cost options.

8.2.3 Break-out approach to the optical channel monitor specification

Another approach is to break out the optical channel monitor performance by isolating each of the operating conditions to the degree possible or practical, and as relevant to the application. One example is to separate out the SOP from the operating conditions and specify a separate budget for polarization dependent loss (PDL). Then the power accuracy and PDL specifications can be added for applications that require fast response time. For applications where the stability of the signal is monitored over a long period of time, only the average fluctuations are of interest, and therefore the PDL specification does not necessarily need to factor in the power accuracy requirement.