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STANDARDIZATION SECTOR
OF ITU

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SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics – Characteristics of optical systems

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Physical transfer functions of optical network elements

ITU-T Recommendation G.680

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ITU-T Recommendation G.680

Physical transfer functions of optical network elements

Summary

ITU-T Recommendation G.680 defines a "degradation function" of optical network elements (ONEs) such as photonic cross-connects (PXCs), optical add-drop multiplexers (OADMs), etc. making up an optical network. This is done in terms of a list of parameters which characterize physical impairments such as optical noise, chromatic dispersion, etc., and is intended to be independent from the network architecture that the devices are deployed in. For each kind of ONE considered in this Recommendation, the general functional description and the reference diagram is provided. Principles for calculating the effect of cascading multiple ONEs on the degradation of the optical signal quality are given and example transfer parameter values for OADMs and PXCs are also provided.

This version of the Recommendation covers the situation where the optical path between two consecutive electrical regenerators is composed of dense wavelength division multiplexing (DWDM) line segments from a single vendor and OADMs and PXCs from other vendors.

Source

ITU-T Recommendation G.680 was approved on 29 July 2007 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

FOREWORD

The International Telecommunication Union (ITU) is the United Nations specialized agency in the field of telecommunications. The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organ of ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis.

The World Telecommunication Standardization Assembly (WTSA), which meets every four years, establishes the topics for study by the ITU-T study groups which, in turn, produce Recommendations on these topics.

The approval of ITU-T Recommendations is covered by the procedure laid down in WTSA Resolution 1.

In some areas of information technology which fall within ITU-T's purview, the necessary standards are prepared on a collaborative basis with ISO and IEC.

NOTE

In this Recommendation, the expression "Administration" is used for conciseness to indicate both a telecommunication administration and a recognized operating agency.

Compliance with this Recommendation is voluntary. However, the Recommendation may contain certain mandatory provisions (to ensure e.g. interoperability or applicability) and compliance with the Recommendation is achieved when all of these mandatory provisions are met. The words "shall" or some other obligatory language such as "must" and the negative equivalents are used to express requirements. The use of such words does not suggest that compliance with the Recommendation is required of any party.

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As of the date of approval of this Recommendation, ITU had not received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementers are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database at http://www.itu.int/ITU-T/ipr/.

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Introduction

The present optical transport networks (OTN) are evolving towards optical networks with an ever decreasing number of O/E/O conversions within their boundaries. The two main reasons for this evolution are the following:

i) DWDM systems are becoming capable of transporting light signals for some thousands of kilometres without electrical regeneration;

ii) Photonic cross-connects (PXC) and optical add/drop multiplexers (OADMs) are becoming available with capacity, space requirements, power consumption, reliability and cost, suitable for their use in the telecommunication networks.

This evolution will lead to the deployment of a domain of optical transparency that can be large enough to ensure that all the potential routes of the backbone network of a medium size country (optical paths up to around 2000 km) could be realized all optically.

ITU-T Recommendation G.680

Physical transfer functions of optical network elements

1 Scope

The scope of this Recommendation is to define a "degradation function" of the optical network elements (DWDM line segment, PXC, OADM, etc.) between points MPI-S_M and MPI-R_M (Figures 6-1 to 6-3) in terms of ASE, non-linear impairment, chromatic dispersion, PMD, etc., independently from the network architecture/structure/configuration that the system is deployed in.

These degradation functions are the basis for guidelines found in clause 8 for the consequence of the cascading of optical network elements (not including DWDM line segments for Situation 1 as described below) within an optical transmission system in order to assess the degradation of the signal quality due to the optical path between the ingress and egress 3R electrical regenerators.

This version of the Recommendation covers the reference situation:

Situation 1 – The optical path between two consecutive 3R regenerators is composed of DWDM line segments from a single vendor and OADMs and PXCs from another vendor as shown in Figure 1-1.

The information in this Recommendation (when taken together with the corresponding parameters from the DWDM line segments including any non-linear effects) enables the evaluation of the impact on line system performance of the combination of transfer parameters related to the cascaded ONEs inserted in the optical route.

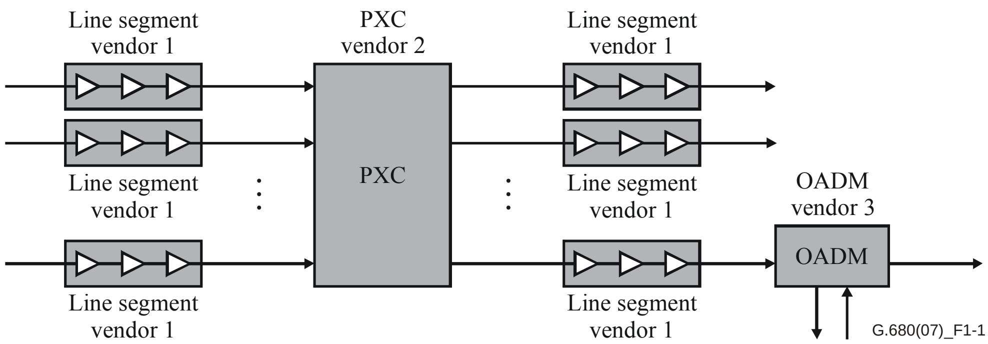

Figure 1-1 – Illustration of Situation 1

A future revision of the Recommendation is expected to cover the reference situation:

Situation 2 – The optical path between two consecutive 3R regenerators is composed of DWDM line segments from different vendors and OADMs and PXCs from different vendors as shown in Figure 1-2.

This will enable the degradation of the signal quality due to the optical path for an arbitrary route through an all-optical network (or sub-network) consisting of optical network elements including DWDM line segments to be assessed thereby enabling routing decisions in an all-optical network (or sub-network) to be made.

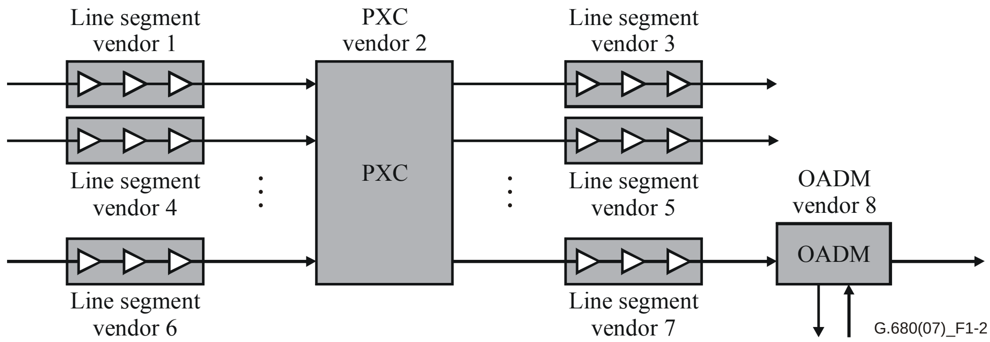

Figure 1-2 – Illustration of situation 2

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T G.652] ITU-T Recommendation G.652 (2005), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.661] ITU-T Recommendation G.661 (2007), *Definition and test methods for the relevant generic parameters of optical amplifier devices and subsystems.*

[ITU-T G.662] ITU-T Recommendation G.662 (2005), *Generic characteristics of optical amplifier devices and subsystems.*

[ITU-T G.663] ITU-T Recommendation G.663 (2000), *Application related aspects of optical amplifier devices and subsystems.*

[ITU-T G.665] ITU-T Recommendation G.665 (2005), *Generic characteristics of Raman amplifiers and Raman amplified subsystems.*

[ITU-T G.666] ITU-T Recommendation G.666 (2005), *Characteristics of PMD compensators and PMD compensating receivers*.

[ITU-T G.667] ITU-T Recommendation G.667 (2006), *Characteristics of adaptive chromatic dispersion compensators*.

[ITU-T G.671] ITU-T Recommendation G.671 (2005), *Transmission characteristics of optical components and subsystems*.

[ITU-T G.694.1] ITU-T Recommendation G.694.1 (2002), *Spectral grids for WDM applications: DWDM frequency grid*.

[ITU-T G.709] ITU-T Recommendation G.709/Y.1331 (2003), *Interfaces for the Optical Transport Network (OTN).*

[ITU-T G.959.1] ITU-T Recommendation G.959.1 (2006), *Optical transport network physical layer interfaces.*

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined in [ITU-T G.661]:

– channel addition/removal (steady-state) gain response;
– channel gain;
– channel input power range;
– channel output power range;
– channel signal-spontaneous noise figure;
– input (or output) power change;
– input reflectance;
– maximum reflectance tolerable at input;
– maximum reflectance tolerable at output;
– maximum total output power;
– multichannel gain variation (inter-channel gain difference);
– multichannel gain-change difference (inter-channel gain-change difference);
– multichannel gain tilt (inter-channel gain-change ratio);
– optical signal-to-noise ratio (OSNR);
– output reflectance;
– rate of change of power;
– total input power range;
– transient duration;
– transient gain increase;
– transient gain reduction.

This Recommendation uses the following term defined in [ITU-T G.663]:

– amplified spontaneous emission (ASE) (see "noise accumulation").

This Recommendation uses the following terms defined in [ITU-T G.671]:

– adjacent channel isolation;
– channel extinction;
– channel frequency range;
– channel insertion loss;
– channel insertion loss deviation;
– dense WDM (DWDM) device;
– differential group delay (see "polarization mode dispersion (PMD)");
– isolation (see "unidirectional (far-end) isolation");
– non-adjacent channel isolation;
– polarization dependent loss (PDL);
– reflectance;
– ripple;

– switching time;

– channel uniformity (see "uniformity").

3.2 Terms defined in this Recommendation

This Recommendation defines the following term:

3.2.1 reconfigure time (for ROADM): The reconfigure time (of an ROADM) is the elapsed time measured from the earliest point that the actuation energy is applied to reconfigure the ONE to the time when the channel insertion loss for all wanted channels has settled to within 0.5 dB of its final steady state value and all other parameters of the device (e.g., isolation and channel extinction) are within the allowed limits.

Here, channel insertion loss for all wanted channels means:

– from the input port to the drop port for all dropped channels;

– from the add port to the output port for all added channels;

– from the input port to the output port for all through channels.

This is illustrated in Figure 3-1.

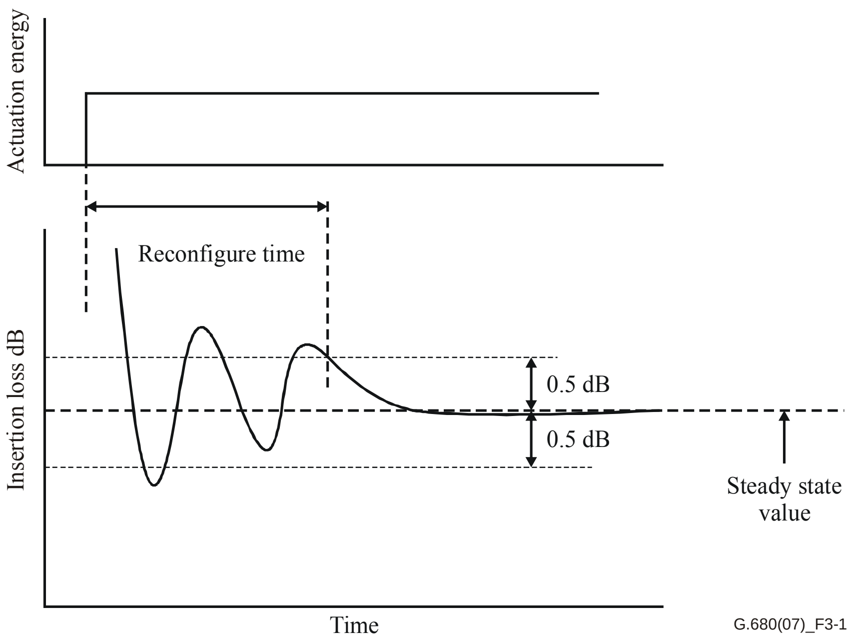

Figure 3-1 – Illustration of reconfigure time

4 Abbreviations

This Recommendation uses the following abbreviations:

2R Re-amplification and Reshaping

3R Re-amplification, Reshaping and Retiming

ADC Adaptive Dispersion Compensator

AGC Automatic Gain Control

AON All-Optical Network

AOWC All-Optical Wavelength Converter

ASE Amplified Spontaneous Emission

BA	Booster-Amplifier
BER	Bit Error Ratio
CD	Chromatic Dispersion
CU	Channel Uniformity
DCM	Dispersion Compensation Module
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fibre Amplifier
FEC	Forward Error Correction
MPI-R	Main Path Interface – Single-channel reference point at the at the ONE input
MPI-R_M	Main Path Interface – Multichannel reference point at the ONE input
MPI-S	Main Path Interface – Single-channel reference point at the ONE output
MPI-S_M	Main Path Interface – Multichannel reference point at the ONE output
NA	Not Applicable
NF	Noise Figure
O/E/O	Optical-Electrical-Optical conversion
OA	Optical Amplifier
OADM	Optical Add/Drop Multiplexer
OD	Optical Demultiplexer
OLA	Optical Line Amplifier
OM	Optical Multiplexer
ONE	Optical Network Element
OSNR	Optical Signal-to-Noise Ratio
OTF	Optical Transfer Function
OTN	Optical Transport Network
OTUk	Completely standardized optical channel transport unit – k
PA	Pre-Amplifier
PDG	Polarization-Dependent Gain
PDL	Polarization-Dependent Loss
PMD	Polarization Mode Dispersion
PMDC	Polarization Mode Dispersion Compensation
PXC	Photonic Cross-Connect
RD	Residual Dispersion
RG	Relative Gain
ROADM	Re-configurable OADM
SOP	State of Polarization
SPM	Self-Phase Modulation

STM Synchronous Transport Module

VOA Variable Optical Attenuator

WDM Wavelength Division Multiplexing

5 Classification of optical network elements

A list of the ONEs which are described by the current version of this Recommendation is:

– DWDM line segment;
– OADM (Fixed and re-configurable optical add/drop multiplexer);
– PXC (photonic cross-connect).

In a future revision of this Recommendation, it is expected that the following ONEs may be added:

– OA (optical amplifier) as a separate ONE rather than inside the ONEs above;
– AOWC (All-optical wavelength converters);
– Optical 3R (optical 3R regenerator);
– Optical 2R (optical 2R regenerator).

6 Reference points

The reference points for DWDM line segments, PXCs and OADMs are illustrated in Figures 6-1 to 6-3, respectively.

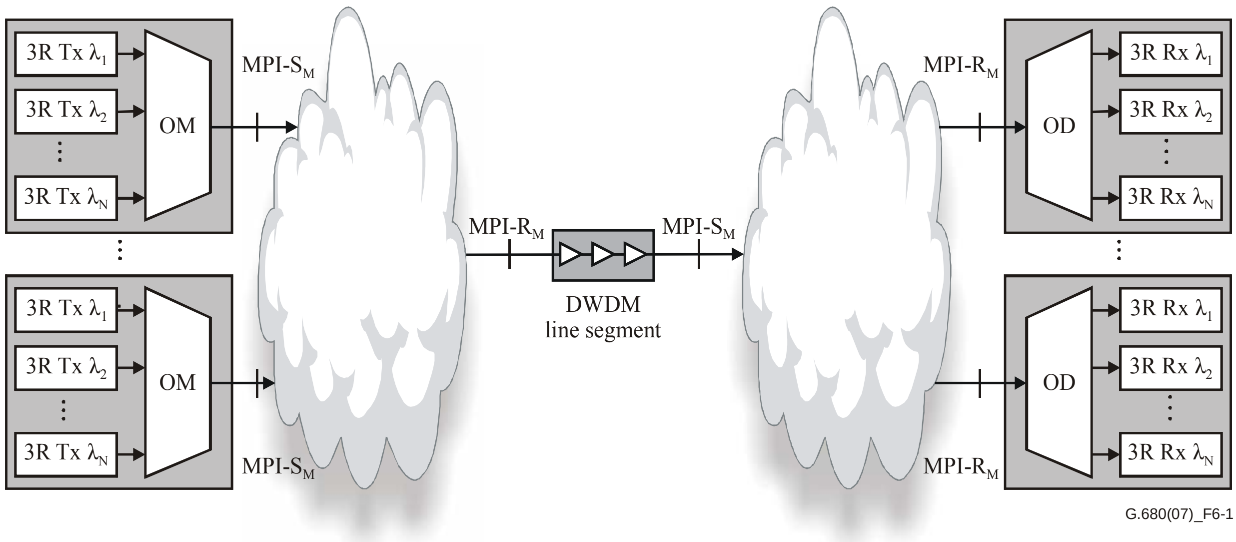

Figure 6-1 – DWDM line segment reference points

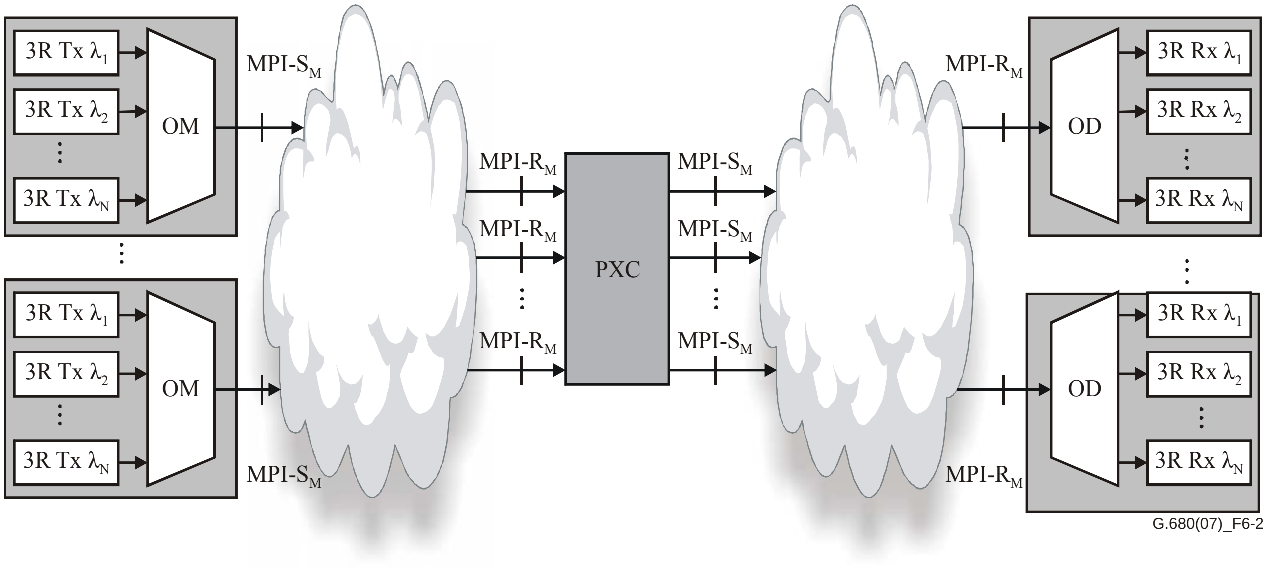

Figure 6-2 – PXC reference points

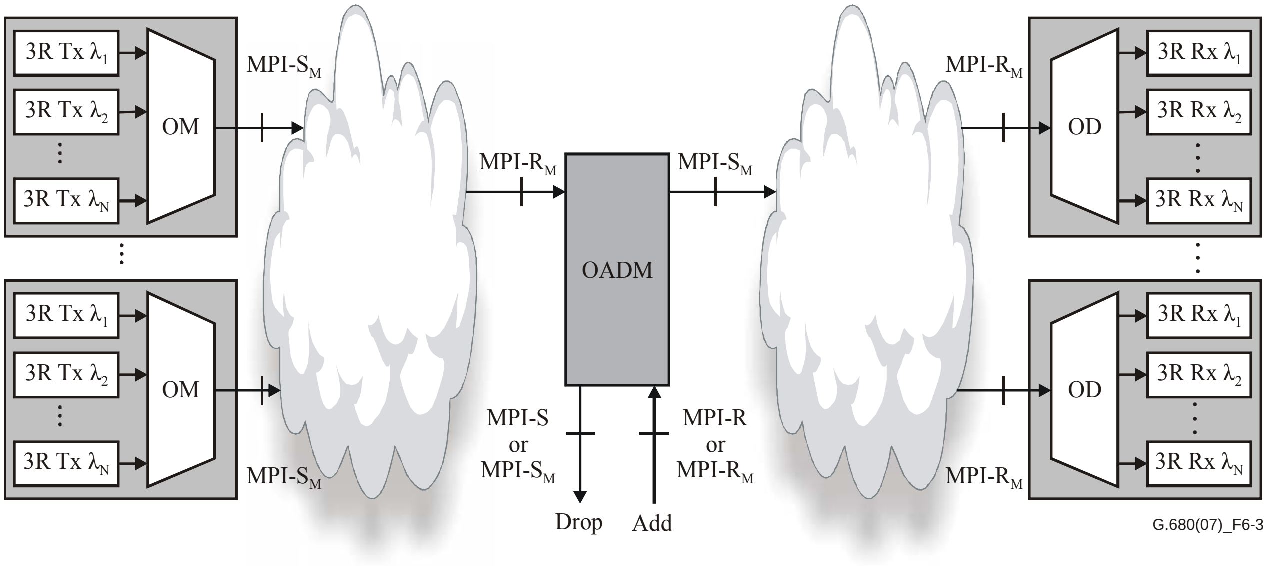

Figure 6-3 – OADM reference points

The reference points in Figures 6-1 to 6-3 are defined as follows:

– MPI-S_M is a multichannel reference point on the optical fibre just after the optical network element transport interface output optical connector;

– MPI-R_M is a multichannel reference point on the optical fibre just before the optical network element transport interface input optical connector;

– MPI-S is a single-channel reference point on the optical fibre just after the OADM output optical connector;

– MPI-R is a single-channel reference point on the optical fibre just before the OADM input optical connector.

7 Functional description of the optical network elements (ONEs)

In this clause, the general functional description and reference diagram is provided for each kind of ONE considered in this Recommendation.

7.1 Functional description of a DWDM line segment

A DWDM line segment is a section of optical transmission fibre together with its associated line amplifiers and any embedded dispersion compensation. This is illustrated in Figure 7-1. The actual arrangement of elements within the DWDM line segment (whether there is an amplifier before the first fibre section or an amplifier after the last fibre section or the placement of any embedded dispersion compensation is not defined).

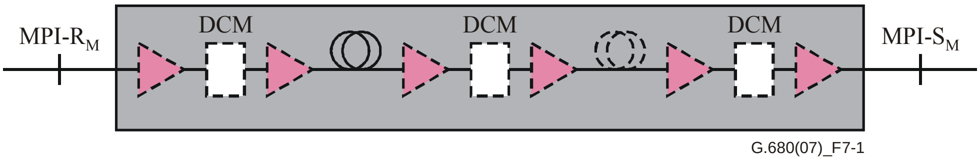

Figure 7-1 – DWDM line segment reference diagram

7.2 Functional description of an OADM (optical add/drop multiplexer)

An OADM is a wavelength selective branching device (used in WDM transmission systems) having a wavelength "drop" function in which one or more signals can be transferred from an input port to either an output port or drop port(s) depending on the wavelength of the signal and also having a wavelength "add" function in which optical signals presented to the add port(s) are also transferred to the output port. The reference diagrams for two variants of OADM are shown in Figures 7-2 and 7-3. For the case illustrated in Figure 7-2, any amplifiers associated with the OADM are considered to be part of the preceding or following line segment, whereas for the case shown in Figure 7-3 they are within the OADM "black-box" and consequently have to be accounted for in the list of transfer parameters.

A re-configurable OADM (ROADM) is an OADM where the wavelengths that are added, dropped and passed through can be dynamically modified (usually remotely).

The arrangement of elements within the OADM black-box shown in Figures 7-2 and 7-3 is not intended to indicate the architecture of the OADM, but simply to define the location of the interfaces. A wide variety of different architectures of OADM are possible and these ONEs may include additional optical functions such as chromatic dispersion compensation (which may be tunable) or PMD compensation, etc.

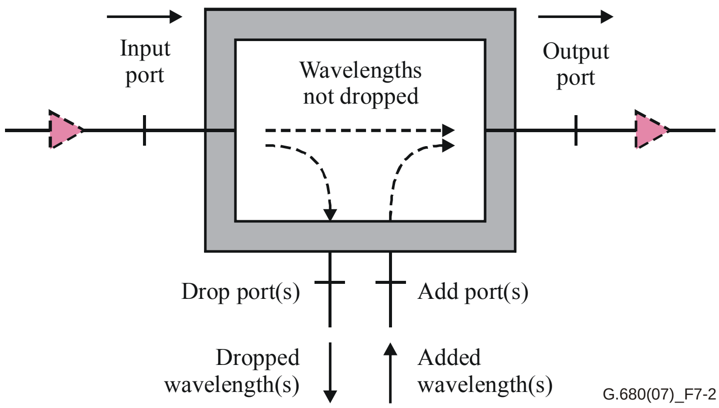

Figure 7-2 – Optical add/drop multiplexer (OADM) reference diagram without amplifiers

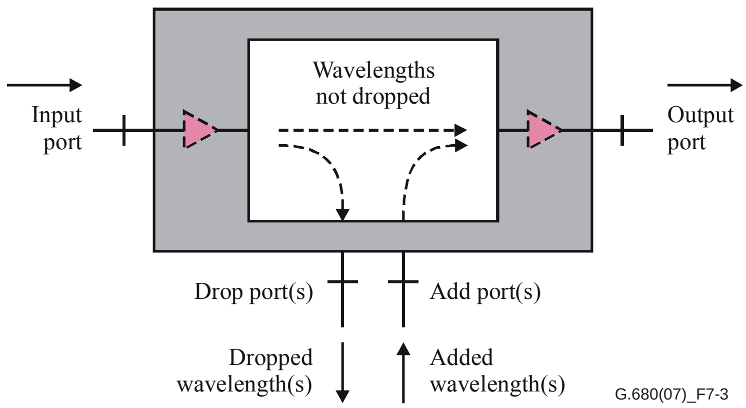

Figure 7-3 – Optical add/drop multiplexer (OADM) reference diagram including amplifiers

7.3 Functional description of a PXC (photonic cross-connect)

The PXC is a (possibly wavelength selective) cross-connect device (used in WDM transmission systems) in which one or more signals can be cross-connected from one of a number of input ports to one of a number of output port(s). The reference diagrams for four variants of PXC are shown in Figures 7-4 to 7-7. Any optical multiplexers or de-multiplexers that are associated with the PXC are considered to be within the PXC "black-box". For the case illustrated in Figure 7-4, any amplifiers associated with the PXC are considered to be part of the preceding or following line segment, whereas for the case shown in Figure 7-5 they are within the PXC "black-box" and consequently have to be accounted for in the list of transfer parameters.

The PXCs illustrated in Figures 7-6 and 7-7 have the additional feature that one or more single channel ports are directly available at the input or output side of the switch, thereby enabling the ONE to additionally perform the function of adding or dropping individual channels.

The arrangement of elements within the PXC black-box shown in Figures 7-4 to 7-7 is not intended to place constraints on the architecture of the PXC, but simply to define the location of the multichannel interfaces. A variety of PXC types are included within this definition such as devices which switch from any input port to any output port:

– any wavelength;
– groups of wavelengths;
– all wavelengths;
– a combination of the above.

Also, these ONEs may include additional optical functions such as chromatic dispersion compensation (which may be tunable) or PMD compensation, etc.

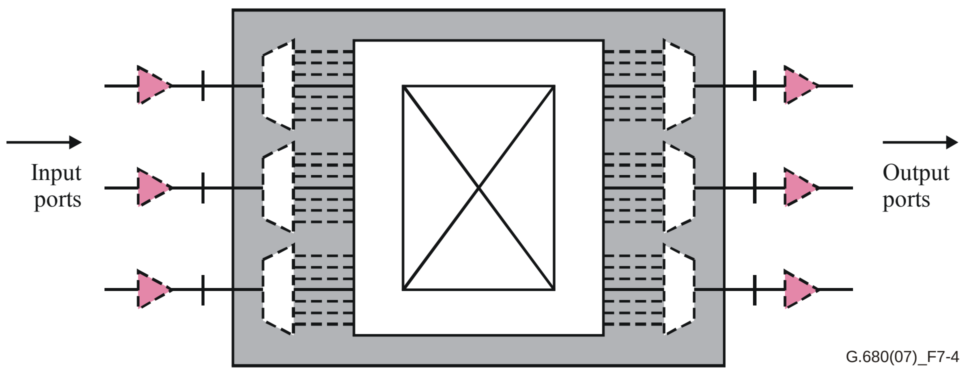

Figure 7-4 – Photonic cross-connect (PXC) reference diagram without amplifiers

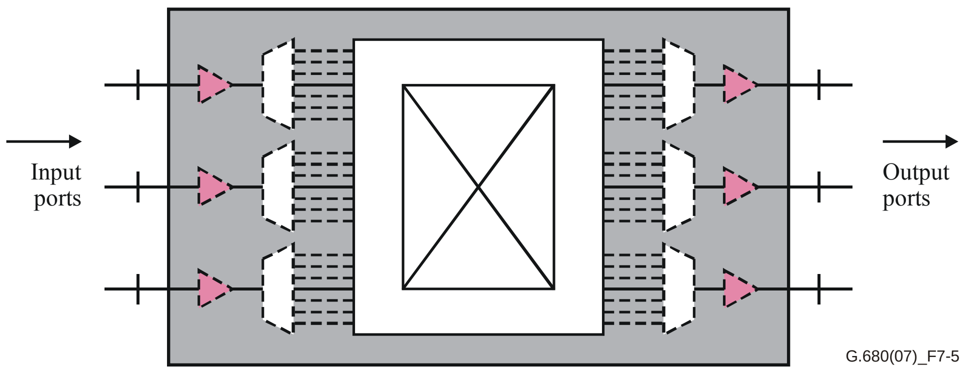

Figure 7-5 – Photonic cross-connect (PXC) reference diagram including amplifiers

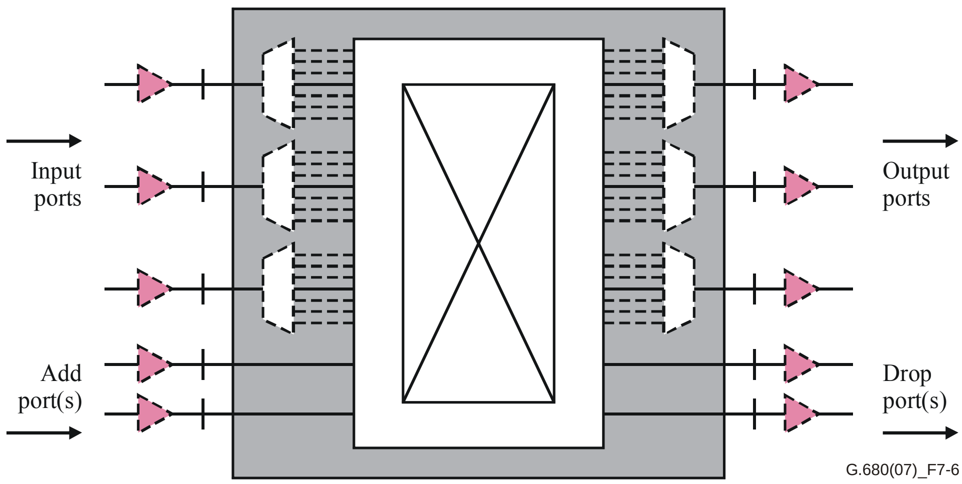

Figure 7-6 – Photonic cross-connect (PXC) with add/drop functions reference diagram without amplifiers

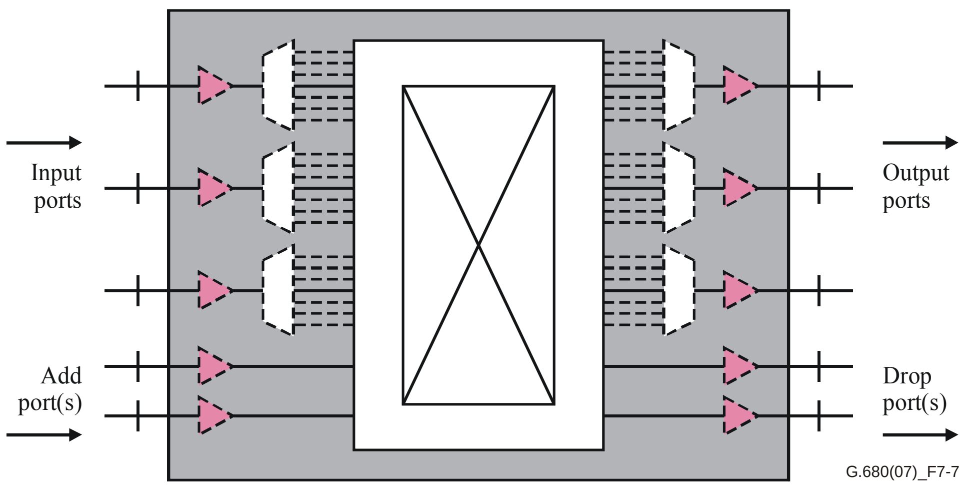

Figure 7-7 – Photonic cross-connect (PXC) with add/drop functions reference diagram including amplifiers

7.4 Functional description of an AOWC (all-optical wavelength converter)

An all-optical wavelength converter (AOWC) is a device that converts the wavelength of an optical channel from one value to another by optical means (i.e., without requiring optical-electrical-optical conversion). Devices that perform this function may operate on multiple channels at once and employ mechanisms such as: cross-gain modulation (XGM), cross-phase modulation (XPM) or four-wave mixing (FWM).

7.5 Functional description of an OA (optical amplifier)

In the current version of this Recommendation optical amplifiers are not included as a separate ONE because, when deployed, they are included in DWDM line segments, ROADMs and/or PXCs.

7.6 Functional description of an optical 3R regenerator

An optical 3R regenerator is a device or sub-system that performs simultaneously in the optical domain the "re-shaping", "re-amplification" and "re-timing" functions on an optical signal. Thus this device or sub-system restores the amplitude of the signal to a level suitable for onward transmission, removes any amplitude noise or distortion present on the waveform and also re-times the signal to remove any timing jitter that may be present.

7.7 Functional description of an optical 2R regenerator

An optical 2R regenerator is a device or sub-system that performs simultaneously in the optical domain the "re-shaping" and "re-amplification" functions on an optical signal. This is generally taken to mean a device that amplifies the optical signal with a non-linear input power to output power transfer curve so as to reduce the amplitude noise or distortion on the optical ones and/or zeros. Any timing jitter on the optical signal, however, is not removed.

8 ONE transfer parameters

A list of ONE optical transfer parameters is given in Table 8-1 for ONEs that do not contain amplifiers. A list of additional parameters that are required for ONEs that do contain amplifiers is given in Table 8-2.

Table 8-1 – ONE transfer parameters for ONEs without amplifiers

Channel frequency range (GHz)
Insertion loss (dB)
Channel insertion loss deviation (dB)
Ripple (dB)
Channel chromatic dispersion (ps/nm)
Differential group delay (ps)
Polarization dependent loss (dB)
Reflectance (dB)
Isolation (dB)
Channel extinction (dB)
Reconfigure time (for ROADM)
Switching time (for PXC)
Channel uniformity
NOTE – Not all parameters apply to all devices.

An additional parameter that may need to be included is the level of multi-path interference. The definition of this parameter and the penalty that it may introduce in cascaded ONEs is left for further study.

Table 8-2 – Additional ONE transfer parameters for ONEs with amplifiers

Total input power range
Channel input power range
Channel output power range
Channel signal-spontaneous noise figure
Input reflectance
Output reflectance
Maximum reflectance tolerable at input
Maximum reflectance tolerable at output
Maximum total output power
Channel addition/removal (steady-state) gain response
Transient duration
Transient gain increase
Transient gain reduction
Channel gain
Multichannel gain-change difference (inter-channel gain-change difference)
Multichannel gain tilt (inter-channel gain-change ratio)

8.1 DWDM line segment transfer parameters

The transfer parameters of a DWDM line segment apply to reference Situation 2 and are for further study.

8.2 OADM transfer parameters

8.2.1 Transfer parameters of OADMs without amplifiers

For the evaluation of the OTF of fixed and re-configurable OADMs without amplifiers, a list of optical transfer parameters is given in Table 8-3 (fixed OADM without amplifiers) and in Table 8-4 (re-configurable OADM without amplifiers).

Table 8-3 – Transfer parameters of fixed OADM without amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel insertion loss Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA

Table 8-3 – Transfer parameters of fixed OADM without amplifiers

Parameter		Max	Min
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to output	dB	NA	
Channel uniformity	dB		NA

Table 8-4 – Transfer parameters of re-configurable OADM without amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel insertion loss Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to output	dB	NA	
Reconfigure time	ms		
Channel uniformity	dB		NA

8.2.2 Transfer parameters of OADMs including amplifiers

For the evaluation of the OTF of fixed and re-configurable OADMs with amplifiers, a list of optical transfer parameters is given in Table 8-5 (fixed OADM with amplifiers) and in Table 8-6 (re-configurable OADM with amplifiers).

Table 8-5 – Transfer parameters of fixed OADM with amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel gain Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to output	dB	NA	
Total input power range	dBm		
Channel input power range Input Add	 dBm dBm		
Channel output power range Output Drop	 dBm dBm		
Channel signal-spontaneous noise figure Input to output Input to drop Add to output	 dB dB dB		 NA NA NA
Input reflectance	dB		NA
Output reflectance	dB		NA
Maximum reflectance tolerable at input	dB	NA	
Maximum reflectance tolerable at output	dB	NA	
Maximum total output power	dBm		NA
Channel addition/removal (steady-state) gain response	dB		
Transient duration	ms		NA
Transient gain increase	dB		NA
Transient gain reduction	dB		NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB		NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB		NA
Channel uniformity	dB		NA

Table 8-6 – Transfer parameters of re-configurable OADM with amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel gain Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to output	dB	NA	
Reconfigure time	ms		NA
Total input power range	dBm		
Channel input power range Input Add	 dBm dBm		
Channel output power range Output Drop	 dBm dBm		
Channel signal-spontaneous noise figure Input to output Input to drop Add to output	 dB dB dB		 NA NA NA
Input reflectance	dB		NA
Output reflectance	dB		NA
Maximum reflectance tolerable at input	dB	NA	
Maximum reflectance tolerable at output	dB	NA	
Maximum total output power	dBm		NA
Channel addition/removal (steady-state) gain response	dB		
Transient duration	ms		NA
Transient gain increase	dB		NA
Transient gain reduction	dB		NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB		NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB		NA
Channel uniformity	dB		NA

8.3 PXC transfer parameters

Even though technologically more complex, the model for a PXC is similar to that of an OADM.

8.3.1 Transfer parameters of PXCs without amplifiers

For the evaluation of the OTF of PXCs without amplifiers, lists of optical transfer parameters are given in Table 8-7 for PXCs without amplifiers and Table 8-8 for PXCs with add/drop functions without amplifiers.

Table 8-7 – Transfer parameters of a PXC without amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel insertion loss input to output	dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Channel extinction input to unwanted output	dB	NA	
Switching time	ms		
Channel uniformity	dB		NA

Table 8-8 – Transfer parameters of a PXC with add/drop functions without amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel insertion loss Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to unwanted output	dB	NA	
Switching time	ms		
Channel uniformity	dB		NA

8.3.2 Transfer parameters of PXCs including amplifiers

For the evaluation of the OTF of PXCs with amplifiers, lists of optical transfer parameters are given in Table 8-9 for PXCs with amplifiers and Table 8-10 for PXCs with add/drop functions and amplifiers.

Table 8-9 – Transfer parameters of a PXC with amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel gain input to output	dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Channel extinction input to unwanted output	dB	NA	
Switching time	ms		
Total input power range	dBm		
Channel input power range	dBm		
Channel output power range	dBm		
Channel signal-spontaneous noise figure	dB		NA
Input reflectance	dB		NA
Output reflectance	dB		NA
Maximum reflectance tolerable at input	dB	NA	
Maximum reflectance tolerable at output	dB	NA	
Maximum total output power	dBm		NA
Channel addition/removal (steady-state) gain response	dB		
Transient duration	ms		NA
Transient gain increase	dB		NA
Transient gain reduction	dB		NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB		NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB		NA
Channel uniformity	dB		NA

Table 8-10 – Transfer parameters of a PXC with add/drop functions and amplifiers

Parameter		Max	Min
Channel frequency range	GHz		
Channel gain Input to output Input to drop Add to output	 dB dB dB		
Channel insertion loss deviation	dB		NA
Ripple	dB		NA
Channel chromatic dispersion	ps/nm		
Differential group delay (DGD)	ps		NA
Polarization dependent loss (PDL)	dB		NA
Reflectance	dB		NA
Adjacent channel isolation input to drop	dB	NA	
Non-adjacent channel isolation input to drop	dB	NA	
Channel extinction input to unwanted output	dB	NA	
Switching time	ms		
Total input power range	dBm		
Channel input power range Input Add	 dBm dBm		
Channel output power range Output Drop	 dBm dBm		
Channel signal-spontaneous noise figure Input to output Input to drop Add to output	 dB dB dB		 NA NA NA
Input reflectance	dB		NA
Output reflectance	dB		NA
Maximum reflectance tolerable at input	dB	NA	
Maximum reflectance tolerable at output	dB	NA	
Maximum total output power	dBm		NA
Channel addition/removal (steady-state) gain response	dB		
Transient duration	ms		NA
Transient gain increase	dB		NA
Transient gain reduction	dB		NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB		NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB		NA
Channel uniformity	dB		NA

8.4 AOWC transfer parameters

The AOWC may be a key device in future AONs. However, at present, they cannot be considered technologically ready to be introduced into the current telecommunication networks. Therefore, a model for their characterization is for further study.

8.5 OA transfer parameters

In the current version of this Recommendation, optical amplifiers are not included as a separate ONE because, when deployed, they are included in DWDM line segments, ROADMs and/or PXCs.

8.6 Optical 3R transfer parameters

The optical 3R regenerators may be a key device in future AONs. However, at present, they cannot be considered technologically ready to be introduced into the current telecommunication networks. Therefore, a model for their characterization is for further study.

8.7 Optical 2R transfer parameters

The optical 2R regenerators too may be a key device in future AONs. However, at present, they cannot be considered technologically ready to be introduced into the current telecommunication networks. Therefore, a model for their characterization is for further study.

9 Impact of the combination of cascaded optical transfer functions on line system performance

9.1 Impact of cascaded ONEs on line system OSNR

In the case that the ONEs considered in this Recommendation contain optical amplifiers, the OSNR of the optical signals at the output or drop ports will be lower than the OSNR at the input or add ports. The magnitude of this reduction can be calculated using equation 9-1.

$$osnr_{out} = \frac{1}{\frac{1}{osnr_{in}} + \frac{1}{osnr_{one}}} \qquad (9\text{-}1)$$

where:

$osnr_{out}$	is the linear OSNR at the output port of the ONE
$osnr_{in}$	is the linear OSNR at the input port of the ONE
$osnr_{one}$	is the linear OSNR that would appear at the output port of the ONE for a noise-free input signal

If the OSNR, etc., is defined in logarithmic terms (dB) and the equation for the OSNR due to the ONE being considered is substituted, this equation becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{OSNR_{in}}{10}\right)} + 10^{-\left(\frac{P_{in} - NF - 10\log(h\nu\nu_r)}{10}\right)}\right) \qquad (9\text{-}2)$$

where:

$OSNR_{out}$	is the log OSNR (dB) at the output port of the ONE
$OSNR_{in}$	is the log OSNR (dB) at the input port of the ONE
P_{in}	is the channel power (dBm) at the input port of the ONE
NF	is the noise figure (dB) of the relevant path through the ONE
h	is Planck's constant (in mJ•s to be consistent with in P_{in} dBm)

ν	is the optical frequency in Hz
ν_r	is the reference bandwidth in Hz (usually the frequency equivalent of 0.1 nm)

NOTE – The terms "P_{in}" and "NF" must be with respect to the same reference point. In the case of an ONE that does not have an amplifier as the first element after the input, any loss between the input of the ONE and the input of the internal amplifier must be accounted for in the value of the noise figure.

This equation can be generalized to account for the OSNR of any end-to-end path through an optical network (including the effect of the amplifiers in the WDM line segments) which results in equation 9-3.

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{P_{in1}-NF_1-10\log(h\nu\nu_r)}{10}\right)} + 10^{-\left(\frac{P_{in2}-NF_2-10\log(h\nu\nu_r)}{10}\right)} + \ldots + 10^{-\left(\frac{P_{inN}-NF_N-10\log(h\nu\nu_r)}{10}\right)}\right) \quad (9\text{-}3)$$

where:

P_{in1}, P_{in2} to P_{inN}	are the channel powers (dBm) at the inputs of the amplifiers or ONEs on the relevant path through the network
NF_1, NF_2 to NF_N	are the noise figures (dB) of the amplifiers or ONEs on the relevant path through the network

The value of $OSNR_{out}$ that is needed to meet the required system BER depends on many factors such as the bit rate, whether and what type of FEC is employed, the magnitude of any crosstalk or non-linear penalties in the DWDM line segments, etc. and is outside the scope of reference Situation 1 within this Recommendation.

An example calculation of the effect on OSNR of cascading multiple ONEs can be found in Appendix II.

9.2 Impact of cascaded ONEs on line system residual dispersion

For most transmitter/receiver combinations in use within current DWDM systems, there is a limited range of end-to-end chromatic dispersion that can be tolerated for satisfactory operation. The actual values of the maximum and minimum tolerable dispersion depend upon the bit rate of transmission as well as the technology employed in the transmitter (e.g., a directly modulated laser generally tolerates less dispersion than an externally modulated source).

So, for any desired path through the optical network, this translates to the requirement that:

$$\textit{Min RD} < \textit{Residual Dispersion} < \textit{Max RD} \quad (9\text{-}4)$$

where:

Residual Dispersion	is the end-to-end dispersion of the desired path through the network within the channel frequency range at all times and temperatures (including the effect of any dispersion compensators in the path
Min RD	is the minimum tolerable residual chromatic dispersion for that transmitter/receiver combination
Max RD	is the maximum tolerable residual chromatic dispersion for that transmitter/receiver combination

In turn, the residual dispersion of a path through the network can be found from:

$$\textit{Residual dispersion} = \sum \textit{fibre dispersion} + \sum \textit{DCM dispersion} + \sum \textit{ONE dispersion} \quad (9\text{-}5)$$

where:

$\sum$ fibre dispersion	is the sum of the dispersions of all of the fibre segments in the path within the channel frequency range
$\sum$ DCM dispersion	is the sum of the dispersions of all of the dispersion compensation modules in the path within the channel frequency range
$\sum$ ONE dispersion	is the sum of the dispersions of all of the optical network elements in the path within the channel frequency range

Generally, both the fibre spans and the DCMs will reside inside the DWDM line segments. However, there are a number of reasons that the dispersion of the fibre spans is not exactly matched by the dispersion of the compensators and these are discussed in clause 9.2.1.

Two alternative approaches can be used to evaluate each of the terms in equation 9-5.

Firstly, a worst-case upper and lower value can be used to generate an upper and lower bound for the residual dispersion at each channel wavelength.

Secondly, in cases where statistical information is available (for instance, the mean and standard deviation of the dispersion of the transmission fibre may be known at the various channel wavelengths), then a statistical approach can be used. An example of this is that if the distribution of total dispersion for that element at a particular wavelength is approximately Gaussian with a mean μ and a standard deviation σ, then an upper limit of $\mu + 3\sigma$ will only be exceeded by ~1 in 1000 links and a lower limit of $\mu - 3\sigma$ will only be exceeded by ~1 in 1000 links.

If statistical information is available for more than one element in equation 9-5, then these elements can be combined statistically. An example of this might be that if the sum of the transmission fibre is known to have a mean μ_f and a standard deviation σ_f, and the sum of the DCMs are known to have a mean μ_c and a standard deviation σ_c at a particular wavelength and the distributions are approximately Gaussian, then an upper limit of $\mu_f + \mu_c + 3\left(\sigma_f^2 + \sigma_c^2\right)^{\frac{1}{2}}$ will only be exceeded by ~1 in 1000 links and a lower limit of $\mu_f + \mu_c - 3\left(\sigma_f^2 + \sigma_c^2\right)^{\frac{1}{2}}$ will only be exceeded by ~1 in 1000 links.

As a consequence of this, if a small probability of the limit being exceeded in a particular path is acceptable, then these values can be used in place of the worst-case maximum and minimum residual dispersion values. The probabilities of the limits $\mu + M\sigma$ and $\mu - M\sigma$ being exceeded are given for a range of multipliers M in Table 9-1.

Table 9-1 – M values and probabilities

Multiplier of standard deviation M	Probability of the limits $\mu + M\sigma$ and $\mu - M\sigma$ being exceeded
2	2.27% (~1 in 50)
3	0.13% (~1 in 1000)
4	0.0032% (~1 in 30'000)

An example calculation of the effect of cascading multiple ONEs on line system residual dispersion can be found in Appendix II.

9.2.1 DWDM line segment residual dispersion

While, in principle, the dispersion compensation modules included within DWDM line segments (or other ONEs such as OADMs or PXCs) cancel the dispersion of the fibre spans, there are several reasons why this is not exact and therefore the residual dispersion of the DWDM line segments must be taken into account in the channel end-to-end residual dispersion. Some of these reasons are:

– The change in dispersion with wavelength is often somewhat different for the transmission fibre than it is for the compensators. This means that if the dispersion of the fibre is exactly matched for a channel in the middle of the multiplex, for channels on the edge there will be a mismatch and therefore a positive residual dispersion at one end and a negative residual dispersion at the other.

– While the dispersion of transmission fibres is fairly tightly constrained, there is a variation in actual dispersion per unit length at a single wavelength due to fibre variability. For example, for G.652 fibre, the dispersion coefficient may vary from 16.9 to 18.2 ps/nm/km at 1550 nm. Likewise, there is a variation from module to module associated with DCMs.

– Dispersion compensation modules are usually only available in a set of values with discrete steps between them. In contrast to this, installation constraints (e.g., hut positions and available rights of way) mean that the span length in a practical system is often quite different from the nominal value leading to residual dispersion at all channel wavelengths.

– In a network where there is more than one possible route between two particular end points, the optical channel may be switched to an alternative route for protection, restoration or maintenance purposes. In this case, while the residual dispersion of the primary path through the network may be acceptable, the residual dispersion of any alternative paths that might be required must also be checked as this may be quite different.

9.3 Impact of cascaded ONEs on line system PMD and PDL

9.3.1 Impact of cascaded ONEs on line system PMD alone

The PMD of an optical fibre cable is specified according to a statistical format that can be combined with the other elements of the optical link to determine a maximum DGD that is defined as a probability limit:

$$DGD\max_{link} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} \qquad (9\text{-}6)$$

where:

$DGD\max_{link}$	is the maximum link DGD (ps)
$DGD\max_F$	is the maximum concatenated optical fibre cable DGD (ps)
S	is the Maxwell adjustment factor (see Table 9-2)
PMD_{Ci}	is the PMD value of the *i*th component (ps)

This equation assumes that the statistics of the instantaneous DGD are approximated by a Maxwell distribution, with the probability of the instantaneous DGD exceeding $DGD\max_{link}$ being controlled by the value of the Maxwell adjustment factor taken from Table 9-2.

Table 9-2 – S values and probabilities

Ratio of max. to mean (S)	Probability of exceeding max.	Ratio of max. to mean (S)	Probability of exceeding max.
3	4.2×10^{-5}	4	7.4×10^{-9}
3.2	9.2×10^{-6}	4.2	9.6×10^{-10}
3.4	1.8×10^{-6}	4.4	1.1×10^{-10}
3.6	3.2×10^{-7}	4.6	1.2×10^{-11}
3.8	5.1×10^{-8}		

Equation 9-6 can be used for calculating the maximum link DGD when several DWDM line segments (possibly with different fibre characteristics) and several ONEs (possibly of different types) are put in cascade.

An example calculation of the effect on PMD of cascading multiple ONEs can be found in Appendix II.

9.3.2 Impact of cascaded ONEs on line system PDL alone

Polarization dependent loss (PDL) is defined in [ITU-T G.671] as the maximum variation of insertion loss due to a variation of the state of polarization (SOP) over all SOPs.

In a long-haul system where many optical network elements are concatenated, the accumulated PDL can cause significant power fluctuation, which could degrade system performance and stability.

Many components or subsystems (filters, OM, OD, gain flattening filters, attenuators, OADM, PXCs, etc.) of DWDM systems can be a source of PDL. Example maximum values of PDL for some of these subsystems can be found in Appendix I and in [ITU-T G.671]. The PDL of single-mode optical fibres is negligible compared to the PDL of components and subsystems. Some characteristics of PDL are:

– PDL can be assumed to be independent from the optical channel bit rate;
– PDL causes power variation along the optical path and degrades the OSNR;
– PDL appears as a random variation in the overall insertion loss of the device;
– The PDL distribution is well approximated by a Maxwellian function if N>>1 (where N is the number of the cascaded components and subsystems).

The Mean PDL value for a cascade of N elements (N>>1) grows according to:

$$Mean\ PDL = \sqrt{\frac{8}{3\pi}} \left[\sum_i PDL_i^2 \right]^{1/2} \ (\text{dB}) \qquad (9\text{-}7)$$

where:

PDL_i is the PDL value of the ith component in dB.

The Maximum PDL value for a cascade of elements can only be defined (as with DGD) as a value with a given probability of being exceeded. Based on the hypothesis of a nearly Maxwellian distribution, the Maximum PDL is given by:

$$Maximum\ PDL = S\sqrt{\frac{3\pi}{8}}\ Mean\ PDL = S \left[\sum_i PDL_i^2 \right]^{1/2} \ (\text{dB}) \qquad (9\text{-}8)$$

where:

S is the Maxwell adjustment factor taken from Table 9-2

When N is limited (i.e., N<5), the statistical approach given above does not hold. As a consequence the PDL distribution is no longer Maxwellian. In this case the Max PDL value due to cascade of N components/or subsystems is given by the following formula:

$$Maximum\ PDL = \sum_i PDL_i \ (\text{dB}) \tag{9-9}$$

An example calculation of the effect on PDL of cascading multiple ONEs can be found in Appendix II.

9.3.3 Impact of cascaded ONEs on a combination of PMD and PDL

The effect of combined PMD and PDL is for further study.

9.4 Impact of cascaded ONEs on line system channel ripple

Many of the ONEs considered in this Recommendation (OADMs, PXCs, etc.) deal with individual channels or sub-bands from the DWDM aggregate and necessarily include filter functions (e.g., ODs, OMs) in order to separate the selected channels from the aggregate input.

Depending on the chosen architecture and implementation technology, there may be one or more filters even in a single ONE, and in a complex optical network, a single channel may experience many of these filters in series before reaching the receiver.

However, cascading these filters can produce a serious effect on the transmitted channel as the transmission functions of the individual filters, in a realistic implementation, concatenate in a way that cannot be simply predicted and which generally tends to produce a narrower spectral window and possible distortion of the optical spectrum with associated transmission penalties.

Two main factors can affect the resulting transmission window: the shape of the filters and their centre frequencies. As an example, flat top filters behave differently from Gaussian-like filters and any further ripple in the transmission range can modify the resulting concatenation. Moreover, some variation in the filter centre frequency is possible, e.g., due to temperature and manufacturing tolerance, provided that the resulting variation of the filter transmission remains within a certain value in the relevant channel frequency range (see definition of "ripple", in [ITU-T G.671]); so, even with ideally Gaussian filters, it is very difficult to predict the results of the concatenation.

The only conclusion that can be drawn on a general basis is that the filter shape resulting from concatenation (effective filter) tends to be progressively narrower and that the edges of the effective filter tend to be progressively steeper. An example calculation of this narrowing and steeping effect can be found in clause II.4, for both flat-top and Gaussian filters. Finally, one more effect can modify the final result in filter cascading: the phase shape of the filters and how these phases sum up.

The narrowing and steepening of the end-to-end filter function tends to produce penalties on the transmission due to the amplitude and phase distortion induced on the transmitted pulse, especially for high bit-rate transmission on a narrow DWDM grid spacing.

In general, the rules by which optical penalty is produced by this filter shrinking depend on the bit rate and modulation format. In particular, the bit-rate and modulation format can determine which power level (below the peak in the transmitter optical spectrum) can be possibly cut by filters with a specified penalty. As an example, in the text of ITU-T Rec. G.698.1 (for 2.5- and 10-Gbit/s metro applications), as long as the power level of –15 dB with respect to the transmitter peak power is within the –2 dB points of the end-to-end filter function, then the optical penalty induced is expected to be below 2 dB. Other values may apply to different situations.

9.5 Impact of cascaded ONEs on line system transients

Optical power transients are sub-millisecond fluctuations in network power levels that are caused by events such as channel loading changes, fibre or device faults, network protection switching, etc. In a dynamic networking environment, optical amplifiers need to be able to compensate for such power variations in order to avoid potential degradation of quality of service to the channels that are not switched. Any rapid power change may be detrimental to service quality e.g., bit error ratio. A reduction in channel power can decrease the optical signal-to-noise ratio, while an increase in the power can enhance degradation due to non-linear effects in transmission fibre. The main factor which determines the gain in erbium-doped fibre amplifiers (EDFAs) is the optical pump power which, together with the input power, determines the inversion level of the optical amplifier at a given pump wavelength. The inversion level of an EDFA characterizes the fraction of erbium atoms that are available to provide energy to the input optical signal, resulting in optical gain. Typically, the inversion level increases with the increase in optical pump power. If wavelengths are added to an EDFA input, increasing its optical input power, the optical power of the pumps will also need to be increased in order to maintain the inversion level and therefore, a constant gain per channel. Similarly, if wavelengths are dropped from an EDFA input, the pumps will need to be rapidly decreased in order to maintain a constant gain per channel which is important to optimize the performance of optical networks.

9.5.1 Types of stimulus

Transients appear in optical networks as a consequence of two categories of stimulus:

i) increase of the optical power at the ONEs as a consequence of bringing into service of new channels or of the rerouting for protection/restoration of some existing optical channels;

ii) decrease of the optical power at the ONEs as a consequence of the removal from service or rerouting of some optical channels or the interruption of some optical channels due to a network fault.

In both of these cases, the stimulus is characterized by two parameters: the input power change (dB) and the rate of change of power (dB/ms). Figure 9-1 illustrates these two categories. The right side of the figure shows a negative input power change (category i) and the left side shows a positive input power change (category ii).

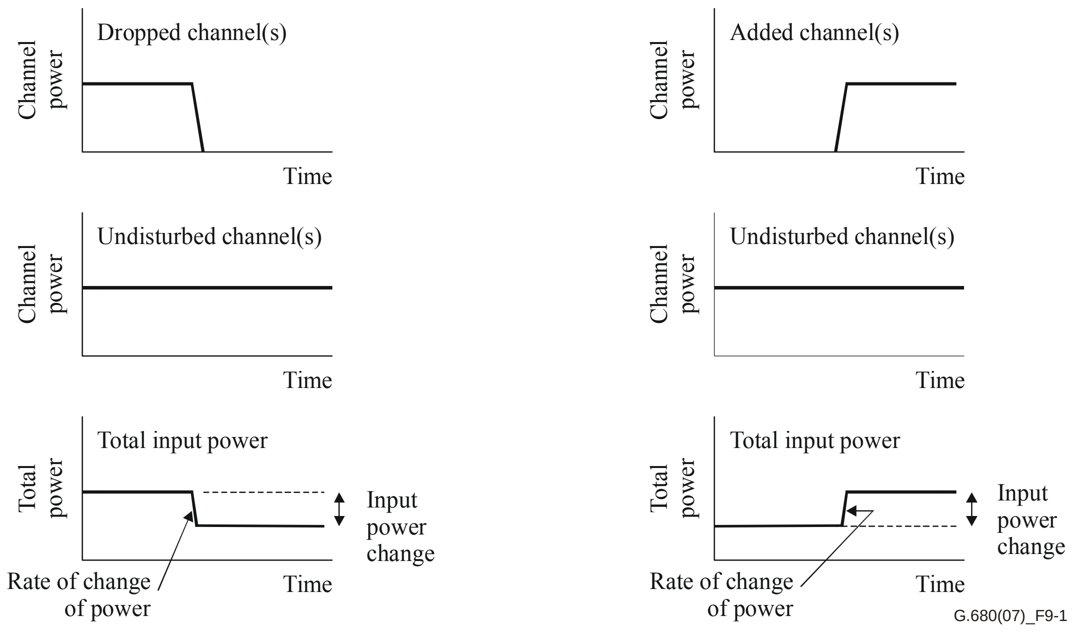

Figure 9-1 – Illustration of the two categories of stimulus

Figure 9-1 shows the total input optical power change caused by simultaneous optical channel changes. There are, however, various patterns of total optical power change created by the superposition of the successive switching of one or more channels that may need to be considered.

One example of this is when the PXC has a redundancy configuration whereby the input optical signals are split between two parallel photonic cross-connect devices as shown in Figure 9-2. In the case of a failure in the working cross-connect device or related components, an output selector switches to the optical signal travelling over the protection path in the PXC. In this case, the total optical power at the output of the PXC may show a reduction (due to the failed channels) for a short time, followed by the total power returning to a value similar to that before the failure.

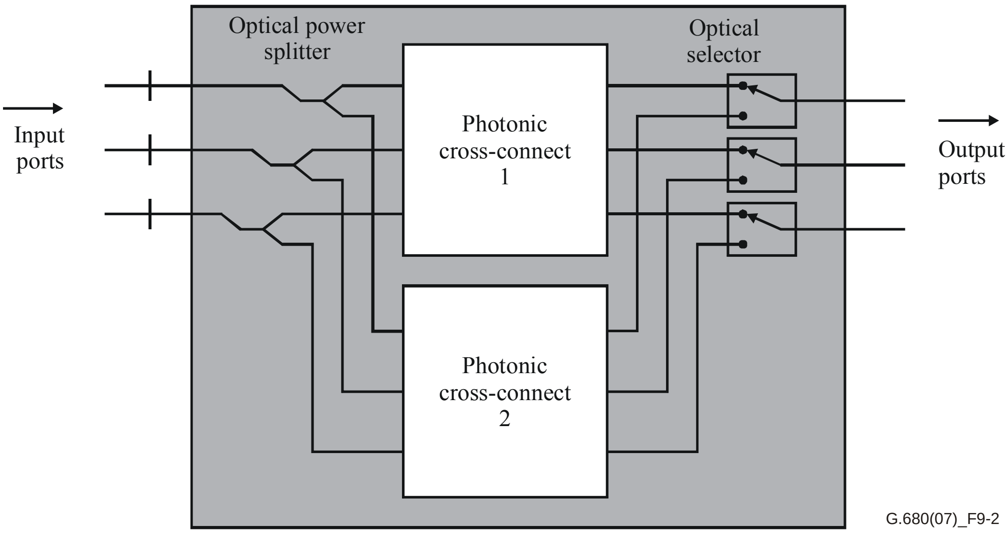

Figure 9-2 – Photonic cross-connect (PXC) with redundancy

9.5.1.1 Bringing into service/removal from service of optical channels

Once a certain optical path (passing through several ROADMs, PXCs and DWDM line segments) has been ascertained as suitable for routing an optical channel and all of the necessary connections in the involved ROADMs and PXCs have been set up, the optical channel can be brought into service. As this happens and the optical power within the new channel rises, the optical power of the pumps of the OAs the channel passes through will have to be increased in order to maintain the inversion level and therefore a constant gain per channel. Any imperfection in this process causes the amplifier gain seen by any undisturbed channels to vary and therefore their power to fluctuate transiently at the activation time of the new channel. The characteristics of the transient induced on the undisturbed channels is related to the time over which the laser switches on in the transmitter and also to the magnitude of the total power change in the amplifiers.

Likewise, when a channel is removed from service, the optical power of the pumps of the OAs that channel passes through will have to be decreased in order to maintain the inversion level and therefore a constant gain per channel. Any imperfection in this process causes the amplifier gain seen by any undisturbed channels to vary and therefore their power to fluctuate transiently at the time that the channel is removed. The characteristics of the transient induced on the undisturbed channels is related to the time over which the laser switches off in the transmitter and also to the magnitude of the total power change in the amplifiers.

9.5.1.2 Fault/protection/restoration

When a fault occurs in an optical network, one or more optical channels may be lost on the operating path while other optical channels may remain undisturbed. Consequently, at the time that the fault occurs, transients may be induced on to the undisturbed channels.

If a channel protection event occurs (e.g., in ring network structures with (R)OADMs), the interrupted channels are activated on a different path (protection path) which may be already set up. In order to minimize the time that the affected channel is unavailable, this activation may be very rapid, thereby inducing transients in other channels at the switching on time of the protection path.

NOTE – In 1+1 protection systems with the two paths simultaneously carrying the signal, the transient in the protection path does not exist.

If a channel restoration event occurs (e.g., in mesh network structures with PXCs) the interrupted channels are activated on a completely different optical path, which is generally already set up, so that transients may be induced in other channels at the switching on time of the protection path.

9.5.2 A cascade of ONEs without optical amplifiers

The cascade of ONEs (OADMs, ROADM and PXC) without amplifiers is a simple case from the point of view of the transients.

In this case the addition/removal of optical channel(s) does not cause transients within the ONEs because they do not have optical amplifiers inside them.

Considering that the ONEs themselves are not involved in the transient generation, the knowledge of the characteristics of the stimulus (power change and rate of change of power) allows the vendor of the DWDM line segments connecting the ONEs to evaluate whether the impact of the transients on the un-switched channels is acceptable.

9.5.3 ONEs with optical amplifiers

The transients in an ONE (OADM, ROADM or PXC) with optical amplifiers that is subjected to a stimulus as described in clause 9.5.1 are characterized by four output parameters:

– channel addition/removal (steady-state) gain response (dB);

– transient duration (ms);

– transient gain increase (dB);

– transient gain reduction (dB).

This is illustrated in Figure 9-3 for the case of channel removal. The left side of the figure shows the stimulus at the input of the ONE and the right side shows two aspects of the response. The upper right graph illustrates the transient induced on one of the undisturbed channels, while the lower right graph shows the total power at the ONE output which may provide the stimulus for the next ONE in the cascade causing it, in turn, to modify the transient induced on the undisturbed channels.

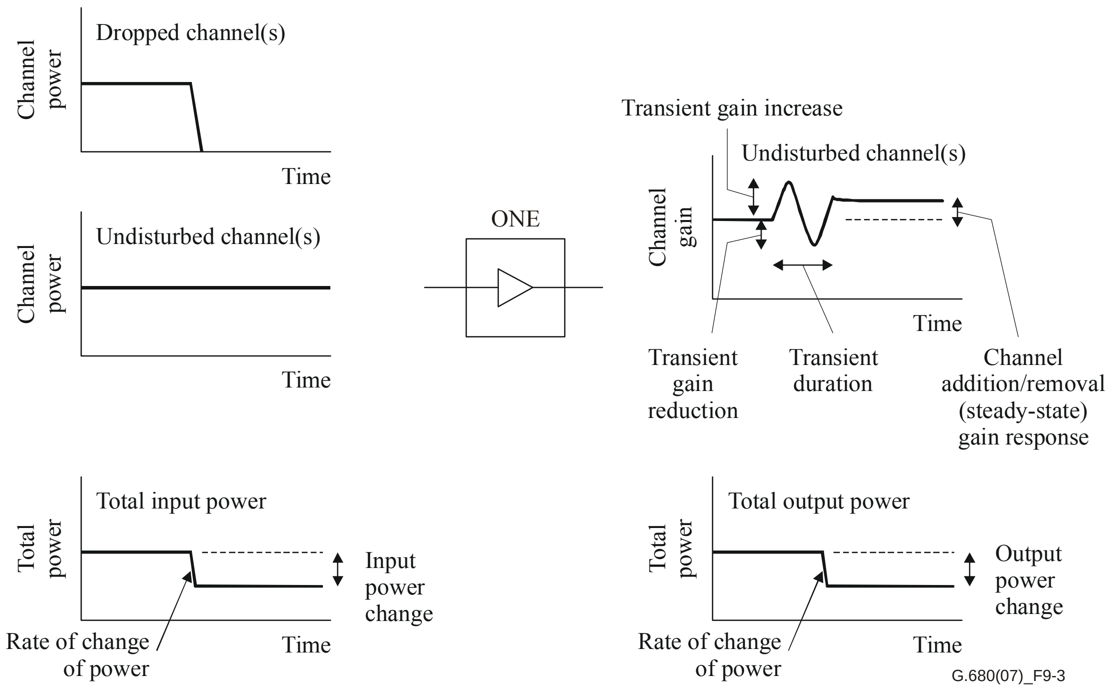

Figure 9-3 – Illustration of optical transients in a single ONE

The values of these parameters allow the vendor of the DWDM line segments following the ONE to understand how much the undisturbed channel has already been affected and also the input conditions for the following line segments in order to evaluate if the impact of the transients on the undisturbed channels is acceptable.

Further discussion of transient effects can be found in clause II.5.

9.5.4 A cascade of ONEs with optical amplifiers

The current version of this Recommendation does not enable the transients at the output of a cascade of ONEs or at a line segment output to be calculated, but rather allows the individual ONE vendor and line segment vendor to evaluate if they are acceptable so providing the operator with sufficient information to decide if induced transients are acceptable for a particular path through the network. This is because these transient calculations are generally not used to decide whether or not to activate or remove a path through the network, but rather to decide whether the transient performance of the network is adequate at the time of construction or when an existing network is extended.

A future version of this Recommendation is expected to deal with the case where the parameters and information in this clause will enable the transients that result from stimulus events in any of the ONEs to be fully characterized.

9.6 Impact of the channel uniformity of cascaded ONEs on line system performance

Channel uniformity (defined as simply "uniformity" in [ITU-T G.671]) is the difference between the highest and lowest channel insertion loss or gain of an ONE.

NOTE – The parameter "Multichannel gain variation (inter-channel gain difference)" defined in [ITU-T G.661] has the same meaning, but is usually applied to optical amplifiers.

In order to accurately assess the impact of the channel uniformity on line system performance, it is necessary to know how much of the variation in loss or gain across the various channels is the same from ONE to ONE and how much is a random variation and therefore different from ONE to ONE.

There are two limiting cases for this:

– case 1: the maximal and minimal channel gains of all of the ONEs on the relevant path through the network correspond to the same two channels;

– case 2: the variation in channel gains of all of the ONEs on the relevant path through the network is entirely random.

In Case 1, because the maximal and minimal channel gains of all of the different ONEs correspond to the same two channels, the end-to-end channel uniformity for a particular path through the network is:

$$\textit{End-to-end channel uniformity} = CU_1 + CU_2 + CU_3 + \ldots + CU_n \quad (9\text{-}10)$$

where:

CU_1	is the channel uniformity of ONE 1
CU_2	is the channel uniformity of ONE 2
CU_3	s the channel uniformity of ONE 3
CU_n	is the channel uniformity of ONE *n*

In Case 2, because the maximal and minimal channel gains may occur on different channels for the various ONEs, the end-to-end channel uniformity for a particular path through the network will usually build up more slowly than for Case 1. The absolute worst-case end-to-end channel uniformity will be the same as for Case 1 (for components with the same maximum channel uniformity specification) but the probability of this happening may be so low that it can safely be disregarded.

For Case 2, the standard deviation of the end-to-end channel uniformity is:

$$\sigma_e = \sqrt{\left(\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots + \sigma_n^2\right)} \quad (9\text{-}11)$$

where:

σ_e	is the standard deviation of the end-to-end channel uniformity
σ_1	is the standard deviation of the channel uniformity of ONE 1
σ_2	is the standard deviation of the channel uniformity of ONE 2
σ_3	is the standard deviation of the channel uniformity of ONE 3
σ_n	is the standard deviation of the channel uniformity of ONE *n*

If the distribution of channel uniformities are Gaussian, then a value of $M\sigma_e$ will have a probability of being exceeded in any link which is the same as is shown in Table 9-1.

When multiple ONEs are cascaded in a real network, the end-to-end channel uniformity lies somewhere between these two cases and equation 9-10 will overestimate it while use of equation 9-11 will produce an underestimate.

If the worst-case channel uniformity is the only information available for the ONEs in a network, then the worst-case end-to-end channel uniformity should be calculated using equation 9-10 since there will be no risk that the actual end-to-end channel uniformity is worse than this.

However, if more detailed information is available for the ONEs, then a more accurate approach that combines the random and non-random parts of the relative channel gains of the ONEs can be used. The information required is the values of the mean and standard deviation of the relative channel gains derived from a large number of each type of ONE. From this information, the relative end-to-end channel gain can be estimated for each channel in turn:

$$\textit{End-to-end channel relative gain} = RG_1 + RG_2 + RG_3 + \ldots + RG_n \quad (9\text{-}12)$$

where:

RG_1	is the relative gain of ONE 1 for that channel
RG_2	is the relative gain of ONE 2 for that channel
RG_3	is the relative gain of ONE 3 for that channel
RG_n	is the relative gain of ONE *n* for that channel

and the end-to-end standard deviation for each channel gain can be found from equation 9-11.

The consequence of the end-to-end channel uniformity being too large is that if some channels have their power significantly higher than others, then the channels with the lowest power at the amplifier inputs risk having an insufficiently high OSNR to meet the BER requirements, while at the same time the channels with the highest power in the transmission fibre risk causing non-linear effects which may compromise the channels in question and/or other channels propagating with them through the same fibre. The actual value where this starts to occur depends upon many design factors such as the number of spans, the values of the span losses, the noise performance of the amplifiers, the channel spacing, the fibre type, etc.

For a system where the end-to-end channel uniformity using a particular set of ONEs is not acceptable, then ONEs with better characteristics must be used, or alternatively the end-to-end channel uniformity can be improved by the addition of one or more dynamic channel equalizers (as described in [ITU-T G.671]) at points in the path where the accumulated channel uniformity has not built up sufficiently to cause excessive reduction in OSNR or non-linearity to occur.

An example calculation of the effect of the channel uniformity for cascaded ONEs on line system performance can be found in Appendix II.

10 Calculation method to combine the system penalty contribution from the impact of the parameters

In clause 9, the impact of cascaded ONEs has been considered for each parameter in isolation from the others. In a practical transmission system, however, the combined effect of all of the impairments on line system performance must be such that the BER objective can be met.

In optical transmission systems that do not contain any optical line amplifiers, the dominant cause of errors is usually electrical noise in the receiver. Consequently, the overall optical budget is usually defined in terms of the lowest difference between the transmitter launch power and the sensitivity of the receiver. This difference is then allocated between the attenuation of the link and the optical path penalty. Writing this as an inequality gives:

$$\textit{Min Tx power} - \textit{Min Rx sensitivity} > \textit{Max attenuation} + \textit{Max optical path penalty} \quad (10\text{-}1)$$

In contrast to this, in this Recommendation which concerns transmission systems that do contain optical line amplifiers the dominant cause of errors is usually ASE noise from the optical amplifiers. This means that the overall optical budget for these systems is defined in terms of OSNR. This can be written as:

$$\textit{Min OSNR} > \textit{Receiver OSNR tolerance} + \textit{Max optical path OSNR penalty} \quad (10\text{-}2)$$

where:

Min OSNR	is the lowest value of OSNR that the signal emerging from the link can have
Receiver OSNR tolerance	is the minimum value of OSNR that the receiver can tolerate (with the required BER) with no impairments due to the path

Max optical path OSNR penalty: is the difference between the OSNR needed to give the required BER at the input and output ends of the end-to-end optical path.

Details of how to calculate the OSNR due to the cascade of optical amplifiers are given in clause 9.1 with an example calculation in clause II.1

However, the actual minimum OSNR that must be accounted for at the output of the link is the worst-case value taking into account the effects of channel uniformity and PDL. Details of how to calculate end-to-end channel uniformity are given in clause 9.6 with an example calculation in clause II.6 and details of how to calculate end-to-end PDL are given in clause 9.3.2 with an example calculation in clause II.3.2. Consequently, the Min OSNR is given by:

$$Min\ OSNR = OSNR - OSNR\ reduction\ from\ channel\ uniformity - OSNR\ reduction\ from\ PDL \quad (10\text{-}3)$$

Similarly, the Max optical path OSNR penalty is made up of contributions from ripple, PMD, residual dispersion and an additional contribution from optical non-linearity. Details of how to calculate end-to-end ripple are given in clause 9.4 with an example calculation in clause II.4, details of how to calculate end-to-end PMD are given in clause 9.3.1 with an example calculation in clause II.3.1 and details of how to calculate end-to-end residual dispersion are given in clause 9.2 with an example calculation in clause II.2.

Because these effects tend to cause eye closure and also because they tend to interact with each other in a non-linear fashion, it is not possible to define a simple equation to calculate the total optical path OSNR penalty. One example of this complex interaction is that a penalty due to self phase modulation (SPM) and a separate penalty due to residual dispersion cannot be simply added together. In fact, under some circumstances these two effects can cancel each other out giving a situation where each effect in isolation gives a large penalty but in combination the total penalty is small.

As a consequence of this, the maximum optical path OSNR penalty must be calculated taking into account:

– the worst-case ripple (clause 9.4);
– the worst-case PMD (clause 9.3.1);
– the worst-case residual dispersion (clause 9.2);
– the non-linear effects in the DWDM line segments which are outside the scope of this version of this Recommendation (situation 1).

An example of how this Recommendation may be applied to a specific application can be found in Appendix III.

Appendix I

Example transfer parameter values

(This appendix does not form an integral part of this Recommendation)

I.1 Example 1 – Values for a re-configurable OADM without amplifiers

Table I.1 represents an example of the transfer parameter values of a re-configurable OADM without amplifiers, with a maximum add/drop capability of 40 channels 100-GHz spaced, 10 Gbit/s each channel and with a channel frequency range of ±12.5 GHz. The general configuration is illustrated in Figure 7-2.

Table I.1 – Transfer parameters of Example 1 – Re-configurable OADM without amplifiers

Parameter		Max	Min
Channel frequency range	GHz	+12.5	–12.5
Channel insertion loss Input to output Input to drop Add to output	 dB dB dB	 15 15 10	 10 10 5
Channel insertion loss deviation	dB	1.5	NA
Ripple	dB	0.6	NA
Channel chromatic dispersion	ps/nm	30	–30
Differential group delay (DGD)	ps	1	NA
Polarization dependent loss (PDL)	dB	1	NA
Reflectance	dB	–30	NA
Adjacent channel isolation input to drop	dB	NA	25
Non-adjacent channel isolation input to drop	dB	NA	35
Channel extinction input to output	dB	NA	40
Reconfigure time	ms	100	1
Channel uniformity	dB	1	NA

I.2 Example 2 – A second set of values for a re-configurable OADM without amplifiers

Table I.2 contains a second example of possible values for the transfer parameter values of a re-configurable OADM without amplifiers, with a maximum add/drop capability of 40 channels 100-GHz spaced, 10 Gbit/s each channel and with a channel frequency range of ±20 GHz. The general configuration is illustrated in Figure I.1.

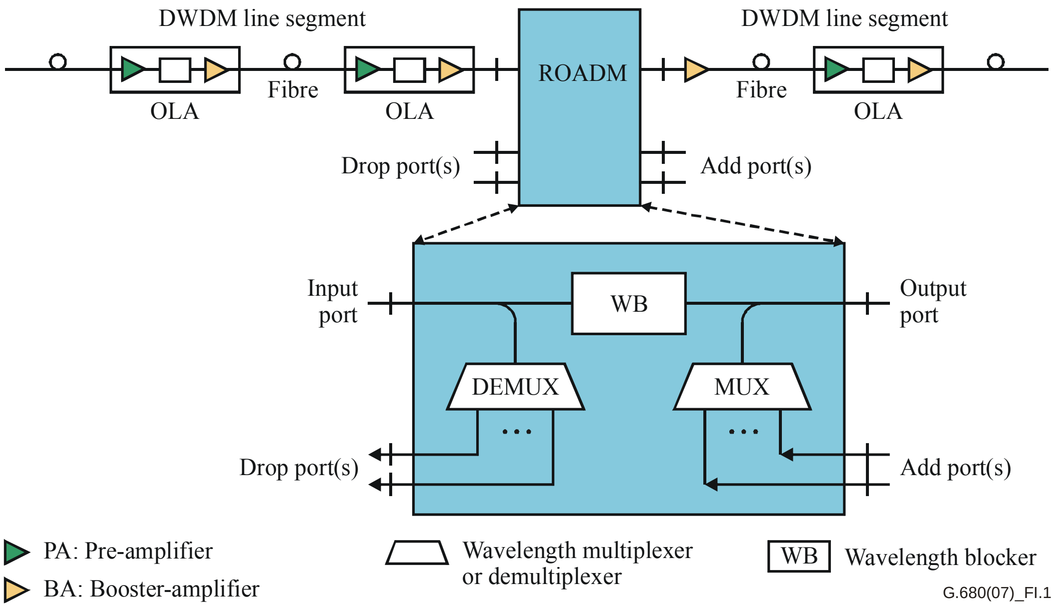

Figure I.1 – Configuration of Example 2 – ROADM without amplifiers

Table I.2 – Transfer parameters of Example 2 – Re-configurable OADM without amplifiers

Parameter		Max	Min
Channel frequency range	GHz	+20	–20
Channel insertion loss Input to output Input to drop Add to output	 dB dB dB	 15 15 12	 10 10 5
Channel insertion loss deviation	dB	1.5	NA
Ripple	dB	0.8	NA
Channel chromatic dispersion	ps/nm	30	–30
Differential group delay (DGD)	ps	1	NA
Polarization dependent loss (PDL)	dB	1	NA
Reflectance	dB	–30	NA
Adjacent channel isolation input to drop	dB	NA	22
Non-adjacent channel isolation input to drop	dB	NA	35
Channel extinction input to output	dB	NA	40
Reconfigure time	ms	100	1
Channel uniformity	dB	2	NA

I.3 Example 3 – Values for a re-configurable OADM with amplifiers

Table I.3 contains example values for the transfer parameters of a re-configurable OADM having nominally unit gain (i.e., having optical amplifiers inside) and placed at the output of an optical line amplifier (OLA) of a DWDM line segment. In particular, the values refer to a re-configurable OADM that does not contain a pre-amplifier at the input to the switching function.

This configuration is illustrated in Figure I.2.

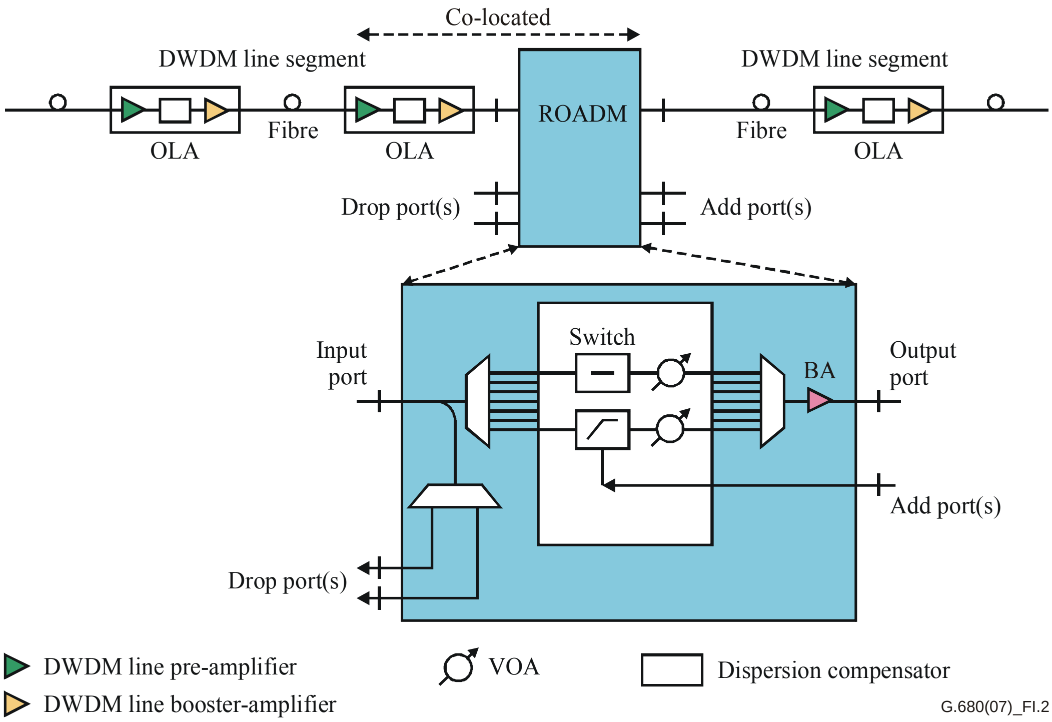

Figure I.2 – Configuration of Example 3 – ROADM with amplifiers

Table I.3 – Transfer parameters of Example 3 – Re-configurable OADM with amplifiers

Parameter		Max	Min
Channel frequency range	GHz	+12.5	–12.5
Channel gain Input to output Input to drop Add to output	 dB dB dB	 +3 –4 +11	 –3 –7 –11
Channel insertion loss deviation	dB	1.5	NA
Ripple	dB	0.6	NA
Channel chromatic dispersion	ps/nm	30	–30
Differential group delay (DGD)	ps	1	NA
Polarization dependent loss (PDL)	dB	1	NA
Reflectance	dB	–30	NA
Adjacent channel isolation input to drop	dB	NA	25
Non-adjacent channel isolation input to drop	dB	NA	35
Channel extinction input to output	dB	NA	40
Reconfigure time	ms	100	1
Total input power range	dBm	+19	–2
Channel input power range Input Add	 dBm dBm	 +3 +6	 –2 –5
Channel output power range Output Drop	 dBm dBm	 +6 –1	 –5 –9

Table I.3 – Transfer parameters of Example 3 – Re-configurable OADM with amplifiers

Parameter		Max	Min
Channel signal-spontaneous noise figure (Note 1) Input to output Input to drop Add to output	 dB dB dB	 22 – 17	 NA NA NA
Input reflectance	dB	–30	NA
Output reflectance	dB	–30	NA
Maximum reflectance tolerable at input	dB	NA	–27
Maximum reflectance tolerable at output	dB	NA	–27
Maximum total output power	dBm	22	NA
Channel addition/removal (steady-state) gain response	dB	1	–1
Transient duration	ms	Note 2	NA
Transient gain increase	dB	Note 2	NA
Transient gain reduction	dB	Note 2	NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB	6	NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB	2	NA
Channel uniformity	dB	2	NA
NOTE 1 – The 22-dB channel signal-spontaneous noise figure input to output of the ROADM is the sum of the loss of the passive components inside the ROADM just after the MPI-S_M point and of the noise figure of the booster amplifier integrated in the ROADM. This might, for example, be made up of a loss of 15 dB (which is compensated by the gain of the following booster amplifier) together with a noise figure of 7 dB. This overall 22 dB has been quoted in Table I.3 in order to avoid having to define the internal structure of the ROADM itself. NOTE 2 – Example transient parameters can be found in Appendix II.			

I.4 Example 4 – A second set of values for a re-configurable OADM with amplifiers

Table I.4 contains a second set of example values for the transfer parameters of a re-configurable OADM having significant gain (i.e., having optical amplifiers inside). In particular the values refer to a re-configurable OADM that contains both a pre-amplifier (PA) at the input to the switching function, and a booster-amplifier (BA) at the output side.

This configuration is illustrated in Figure I.3.

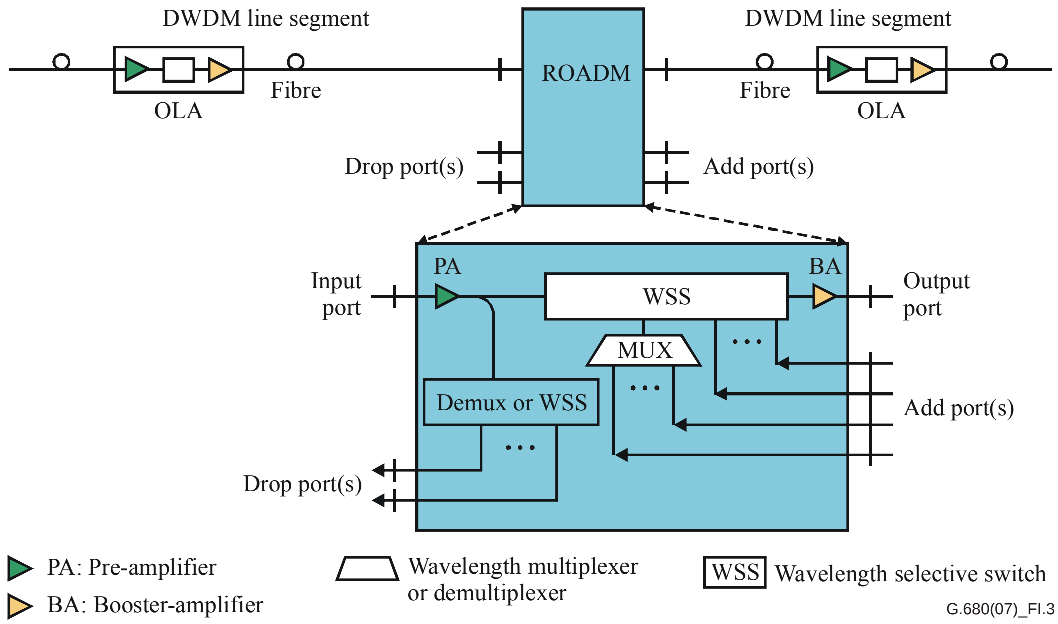

Figure I.3 – Configuration of Example 4 – ROADM with amplifiers

Table I.4 – Transfer parameters of Example 4 – Re-configurable OADM with amplifiers

Parameter		**Max**	**Min**
Channel frequency range	GHz	+12.5	–12.5
Channel gain Input to output Input to drop Add to output	 dB dB dB	 29 15 9	 7 –8 –11
Channel insertion loss deviation	dB	1.5	NA
Ripple	dB	0.5	NA
Channel chromatic dispersion	ps/nm	30	–30
Differential group delay (DGD)	ps	1	NA
Polarization dependent loss (PDL)	dB	1	NA
Reflectance	dB	–30	NA
Adjacent channel isolation input to drop	dB	NA	25
Non-adjacent channel isolation input to drop	dB	NA	35
Channel extinction input to output	dB	NA	40
Reconfigure time	ms	100	1
Total input power range	dBm	+4	–23
Channel input power range Input Add	 dBm dBm	 –12 +6	 –23 –3
Channel output power range Output Drop	 dBm dBm	 +6 –8	 –5 –20

Table I.4 – Transfer parameters of Example 4 – Re-configurable OADM with amplifiers

Parameter		Max	Min
Channel signal-spontaneous noise figure (Note 1) Input to output Input to drop Add to output	 dB dB dB	 12 6 24	 NA NA NA
Input reflectance	dB	–30	NA
Output reflectance	dB	–30	NA
Maximum reflectance tolerable at input	dB	NA	–27
Maximum reflectance tolerable at output	dB	NA	–27
Maximum total output power	dBm	+22	NA
Channel addition/removal (steady-state) gain response	dB	1.5	–1.5
Transient duration	dB	Note 2	NA
Transient gain increase	dB	Note 2	NA
Transient gain reduction	ms	Note 2	NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB	6	NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB	2	NA
Channel uniformity	dB	3	NA
NOTE 1 – For the ROADM including the PA and BA as shown in Figure I.3, the preceding fibre loss is compensated by the gain of the PA inside the ROADM, the loss of the components inside ROADM is compensated by the gain of the BA. Channel signal-spontaneous noise figure of input to output of the ROADM is the integrated result of the noise figures of the PA and BA and the maximum insertion loss in between. Channel signal-spontaneous noise figure of add to output is related to the noise figure of the BA and the insertion loss of the added signals. NOTE 2 – Example transient parameters can be found in Appendix II.			

I.5 Example 5 – Values for a PXC with add/drop functions and amplifiers

Table I.5 contains example values for the transfer parameters of a PXC having nominally unit gain (i.e., having optical amplifiers inside) and placed at the output of an optical line amplifier of a DWDM line segment. In particular, the PXC does not contain a pre-amplifier at the input to the switching function. Moreover, the values refer to a PXC with add/drop functions inside and a capacity of at least 120 OTU2 bidirectional channels. This configuration is illustrated in Figure I.4.

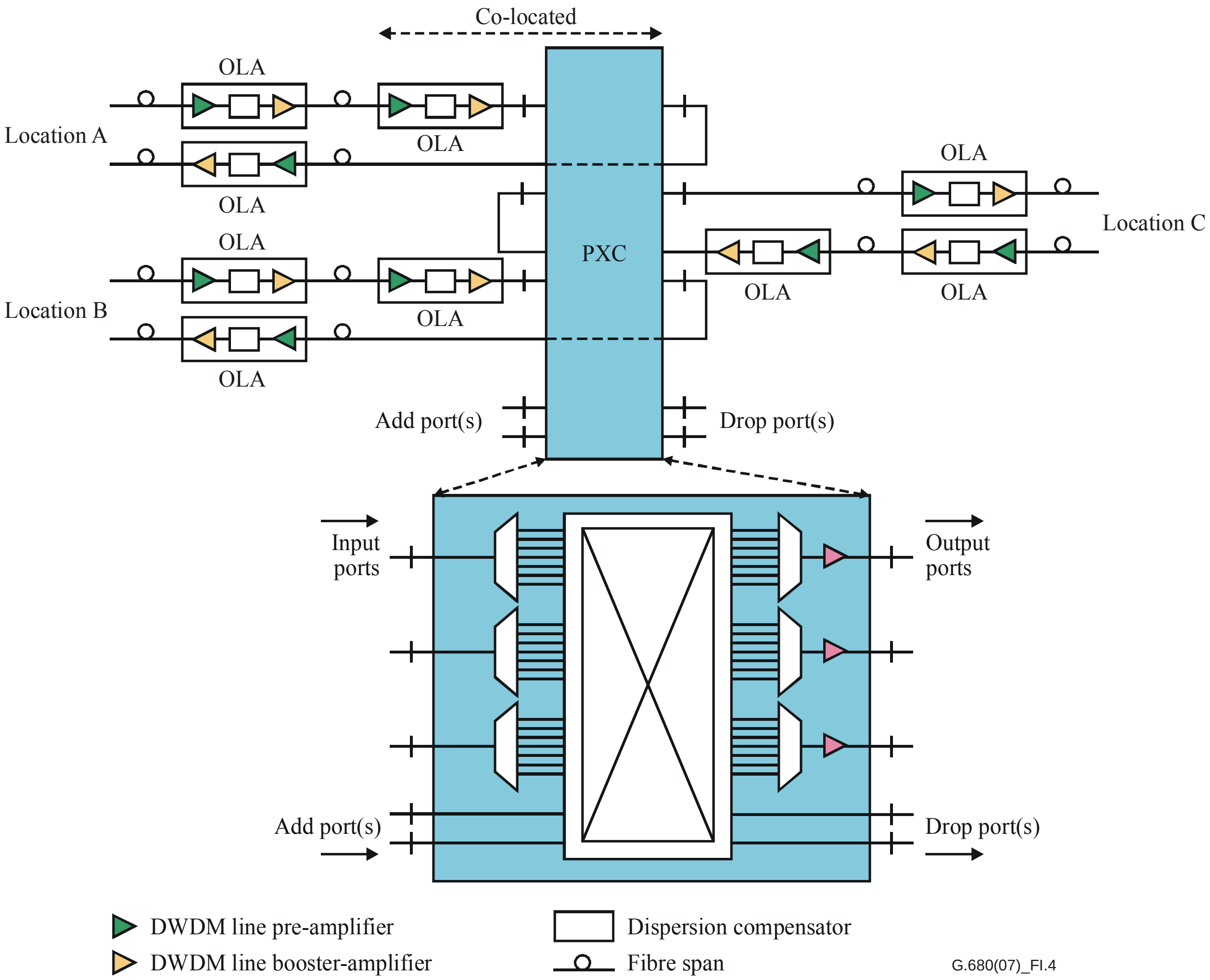

Figure I.4 – Configuration of Example 5 – PXC with amplifiers

Table I.5 – Parameters of Example 5 – PXC with add/drop functions for 120 OTU2 bidirectional channels including optical amplifier

Parameter		Max	Min
Channel frequency range	GHz	+12.5	–12.5
Channel gain Input to output Input to drop Add to output	 dB dB dB	 +1.0 –6.0 +7.0	 –1.0 –20.0 –7.0
Channel insertion loss deviation	dB	1.0	NA
Ripple	dB	1.0	NA
Channel chromatic dispersion	ps/nm	30	–30
Differential group delay (DGD)	ps	3.0	NA
Polarization dependent loss (PDL)	dB	1.5	NA
Reflectance	dB	–40	NA
Adjacent channel isolation input to drop	dB	NA	25
Non-adjacent channel isolation input to drop	dB	NA	35
Channel extinction input to unwanted output	dB	NA	40

Table I.5 – Parameters of Example 5 – PXC with add/drop functions for 120 OTU2 bidirectional channels including optical amplifier

Parameter		Max	Min
Switching time	ms	10	1
Total input power range	dBm	+21	–2
Channel input power range Input Add	 dBm dBm	 +5 +5	 –2 –2
Channel output power range Output Drop	 dBm dBm	 +5 –8	 –2 –20
Channel signal-spontaneous noise figure (Note 1) Input to output Input to drop Add to output	 dB dB dB	 20 – 20	 NA NA NA
Input reflectance	dB	–27	NA
Output reflectance	dB	–40	NA
Maximum reflectance tolerable at input	dB	NA	–24
Maximum reflectance tolerable at output	dB	NA	–10
Maximum total output power	dBm	+21	NA
Channel addition/removal (steady-state) gain response 3 dB 9 dB 15 dB	dB	+0.3 +0.5 +1.0	–0.3 –0.5 –1.0
Transient duration	ms	Note 2	NA
Transient gain increase	dB	Note 2	NA
Transient gain reduction	dB	Note 2	NA
Multichannel gain-change difference (inter-channel gain-change difference)	dB	6	NA
Multichannel gain tilt (inter-channel gain-change ratio)	dB/dB	2	NA
Channel uniformity	dB	3	NA

NOTE 1 – The 20-dB channel signal-spontaneous noise figure input to output of the PXC is the sum of the loss of the passive components inside the PXC just after the MPI-S_M point and of the noise figure of the booster amplifier integrated in the PXC. This might, for example, be made up of a loss of 13 dB (which is compensated by the gain of the following booster amplifier) together with a noise figure of 7 dB. This overall 20 dB has been quoted in Table I.5 in order to avoid having to define the internal structure of the PXC itself.

NOTE 2 – Example transient parameters can be found in Appendix II.

Appendix II

Examples of the effects of cascading ONEs

(This appendix does not form an integral part of this Recommendation)

II.1 Example of the impact of cascaded ONEs on line system OSNR

In order to illustrate the effect of multiple ONEs on line system OSNR, an example system is shown in Figure II.1

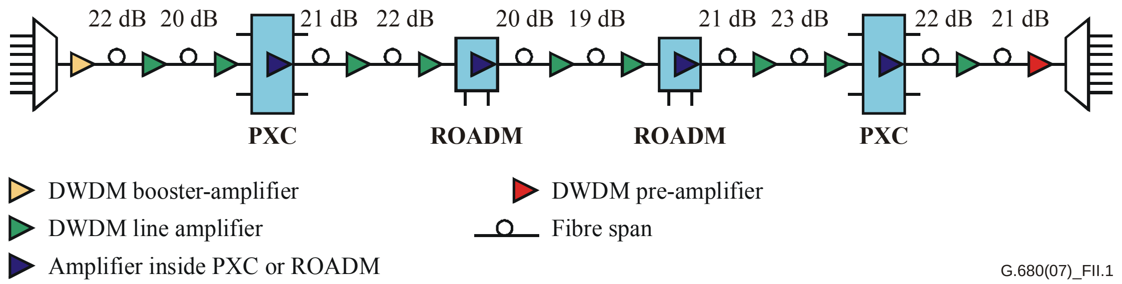

Figure II.1 – Configuration of OSNR example system

This example also assumes:

- The characteristics of the ROADMs are taken from the example found in Table I.3.
- The characteristics of the PXCs are taken from the example found in Table I.5.
- The channel output powers of all of the amplifiers is +1 dBm.
- The noise figures of the booster, line and pre-amplifiers are 7 dB.
- The gain of the booster amplifier is 10 dB.

From Table I.3 the channel signal-spontaneous noise figure for the ROADMs is 22 dB. This value takes account of the loss of the ROADM between the input port and the input of the booster amplifier at the ROADM output (see Figure I.2).

Likewise, from Table I.5 the channel signal-spontaneous noise figure for the PXCs is 20 dB.

In order to calculate the OSNR expected at the output of the demux for a channel wavelength of say 1550.12 nm (193.4 THz) equation 9-3 can be applied. The element of this equation $10\log(h\nu\nu_r)$ for ν = 193.4 THz and ν_r = 12.48 GHz (0.1 nm) equals –58.0 dBm

Equation 9-3 then becomes:

$$OSNR_{out} = -10\log\left(10^{-\left(\frac{-9-7+58}{10}\right)} + 10^{-\left(\frac{-21-7+58}{10}\right)} + 10^{-\left(\frac{-19-7+58}{10}\right)} + 10^{-\left(\frac{1-20+58}{10}\right)} + \ldots + 10^{-\left(\frac{-20-7+58}{10}\right)}\right)$$

with the values used for each term for P_{in} and NF as summarized in Table II.1. Also shown in Table II.1 are the resulting OSNR values at the output of each amplifier.

Table II.1 – OSNR example summary

	Booster	Line1	Line2	PXC1	Line3	Line4	OADM1	Line5	Line6	OADM2	Line7	Line8	PXC2	Line9	Pre1
P_{in} dBm	–9	–21	–19	1	–20	–21	1	–19	–18	1	–20	–22	1	–21	–20
NF dB	7	7	7	20	7	7	22	7	7	22	7	7	20	7	7
Output OSNR	42.0	29.7	27.7	27.4	25.8	24.4	24.1	23.5	23.0	22.8	22.2	21.4	21.3	20.8	20.4

Hence, the OSNR at the output of the demux for the 1550.12-nm channel would be 20.4 dB for this system.

II.2 Example of the impact of cascaded ONEs on line system residual dispersion

In order to illustrate the effect of multiple ONEs on line system residual dispersion, an example system is shown in Figure II.2.

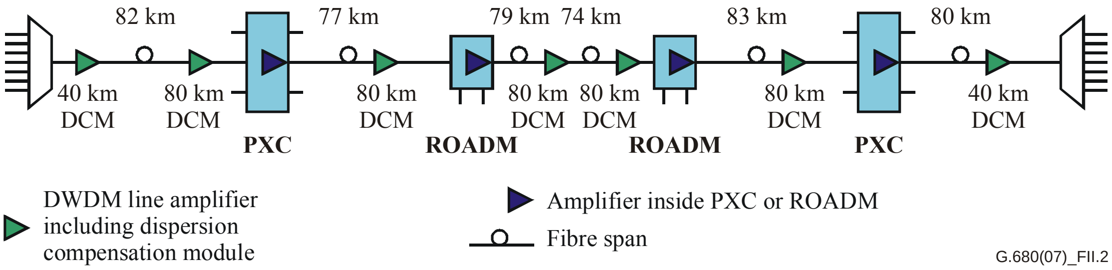

Figure II.2 – Configuration of residual dispersion example system

This example also assumes:

– The characteristics of the ROADMs are taken from the example found in Table I.3.

– The characteristics of the PXCs are taken from the example found in Table I.5.

– The fibre spans are made up with G.652-type fibre.

– There are 40 channels from 195.8 to 191.9 THz (1531.12 to 1562.23 nm).

– The transmitter/receiver combination in use can tolerate between –500 and +1000 ps/nm of dispersion with acceptable OSNR penalty.

Channels that pass all the way from the multiplexer on the left of Figure II.2 to the demultiplexer on the right pass through a total of 475 km of G.652 fibre, two 40-km DCMs, five 80-km DCMs, two PXCs and two ROADMs.

Starting with a worst-case evaluation of the elements of equation 9-5, from [ITU-T G.652] we can estimate the dispersion of the fibre at the two extreme wavelengths and a central wavelength as shown in Table II.2.

Table II.2 – Dispersion limits for 475 km of G.652 fibre

Channel wavelength (nm)	Min (ps/nm)	Max (ps/nm)
1531.12	7455	8122
1546.92	7916	8563
1562.23	8352	8980

An example of the possible dispersion characteristics of the two types of dispersion compensators are shown in Table II.3.

Table II.3 – Possible dispersion of 40- and 80-km DCM modules

Channel wavelength (nm)	40 km DCM		80 km DCM	
	Min (ps/nm)	Max (ps/nm)	Min (ps/nm)	Max (ps/nm)
1531.12	–639	–607	–1278	–1215
1546.92	–677	–644	–1355	–1288
1562.23	–716	–680	–1431	–1361

From Table I.3 for the ROADMs and Table I.5 for the PXCs the dispersion of these ONEs is between –30 and +30 ps/nm each. So, applying equation 9-5 for the case of minimum and maximum dispersion at 1531.12 nm we have:

1531.12 nm minimum residual dispersion = 7455 + 2 × –639 + 5 × –1278 + 4 × –30 = –333 ps/nm

1531.12 nm maximum residual dispersion = 8122 + 2 × –607 + 5 × –1215 + 4 × 30 = 953 ps/nm

These results and those for the other wavelengths are summarized in Table II.4.

Table II.4 – Maximum and minimum end-to-end residual dispersion values

Channel wavelength (nm)	Min (ps/nm)	Max (ps/nm)
1531.12	–333	953
1546.92	–331	956
1562.23	–355	934

So, since the transmitter/receiver combinations used on these links can tolerate between –500 and +1000 ps/nm with acceptable OSNR penalty, the condition in equation 9-4 is met and these paths have acceptable residual dispersion.

The example above uses a worst-case approach based on limiting dispersion values of G.652 fibre. If statistical information was available for the transmission fibre and the 80-km DCMs (but not the 40-km DCMs or the ONEs where the worst-case information is maintained), then this example might be re-calculated as shown below.

Additional statistical information assumed:

– The characteristics of each 5-km segment of the transmission fibre are:
  - mean dispersion 82.7 ps/nm and standard deviation 1.68 ps/nm at 1531.12 nm;
  - mean dispersion 87.5 ps/nm and standard deviation 1.62 ps/nm at 1546.92 nm;
  - mean dispersion 92.1 ps/nm and standard deviation 1.58 ps/nm at 1562.23 nm.
– The characteristics of the 80-km DCMs are:
  - mean dispersion –1246 ps/nm and standard deviation 10.5 ps/nm at 1531.12 nm;
  - mean dispersion –1321 ps/nm and standard deviation 11.1 ps/nm at 1546.92 nm;
  - mean dispersion –1396 ps/nm and standard deviation 11.7 ps/nm at 1562.23 nm.
– A probability of ~1 in 1000 (equivalent to a standard deviation multiplier of 3) of the calculated minimum and maximum residual dispersion values being exceeded is acceptable to the operator.

To obtain a total of 475 km of transmission fibre, we need 475/5 = 95 segments of 5 km each. Therefore, the total dispersion of 475 km of fibre with the characteristics shown above will have a mean dispersion of 95 × 82.7 ps/nm = 7856.5 ps/nm and a standard deviation of $\sqrt{95} \times 1.68 = 16.4$ ps/nm at 1531.12 nm (since the standard deviation of n copies of a random variable added together has a standard deviation $\sqrt{n}$ times as large).

The five 80-km DCMs will have a mean dispersion of 5 × –1246 ps/nm = –6230 ps/nm and a standard deviation of $\sqrt{5} \times 10.5 = 23.5$ ps/nm at 1531.12 nm.

Combining these elements as described in clause 9.2 gives:

1531.12 nm Min RD = 7856.5 + 2 × –639 + –6230 + 4 × –30 – 3 × $(16.4^2 + 23.5^2)^{1/2}$ = 143 ps/nm

1531.12 nm Max RD = 7856.5 + 2 × –607 + –6230 + 4 × 30 + 3 × $(16.4^2 + 23.5^2)^{1/2}$ = 618 ps/nm

These results and those for the other wavelengths are summarized in Table II.5.

Table II.5 – Maximum and minimum end-to-end residual dispersion values using some statistical information

Channel wavelength (nm)	Min (ps/nm)	Max (ps/nm)
1531.12	143	618
1546.92	145	628
1562.23	127	620

II.3 Examples of the impact of cascaded ONEs on line system PMD and PDL

II.3.1 Example of the impact of cascaded ONEs on line system PMD alone

In order to illustrate the effect of multiple ONEs on line system PMD, the example system as shown in Figure II.1 can be used. This example also assumes:

- The characteristics of the ROADMs are taken from the example found in Table I.3.
- The characteristics of the PXCs are taken from the example found in Table I.5.
- Each fibre span has a length of 80 km making the total system length 800 km.
- The links are required to operate at the STM-64 rate of 9.95328 Gbit/s and therefore the maximum DGD that should be tolerated is 30 ps.
- A probability of exceeding the maximum DGD of 4.2×10^{-5} is acceptable and hence S = 3.

The DGD value for the ROADMs from Table I.3 is 1 ps and the value for the PXCs from Table I.5 is 3 ps. Equation 9-6 therefore becomes:

$$30\text{ ps} = \left[DGD\max_F^2 + 3^2\left(3^2 + 1^2 + 1^2 + 3^2\right)\right]^{1/2}$$

Rearranging this gives:

$$DGD\max_F = \left[30^2 - 180\right]^{1/2} = 26.8\text{ ps}$$

And, hence, for the 800 km of fibre, the maximum PMD coefficient that can be tolerated is 0.32 ps/$\sqrt{\text{km}}$.

II.3.2 Example of the impact of cascaded ONEs on line system PDL alone

In order to illustrate the effect of multiple ONEs on line system PDL, the example system shown in Figure II.1 can be used. This example also assumes:

– The characteristics of the ROADMs are taken from the example found in Table I.3.
– The characteristics of the PXCs are taken from the example found in Table I.5.
– The PDL of the Mux and Demux is 0.25 dB each.
– The PDL (or PDG) of the 11 line amplifiers is 0.5 dB each.
– A probability of exceeding the maximum PDL of 4.2×10^{-5} is acceptable and hence S = 3.

The PDL value for the two ROADMs from Table I.3 is 1 dB and the value for the two PXCs from Table I.5 is 1.5 dB. Equation 9-7 therefore becomes:

$$\textit{Mean PDL} = \sqrt{\frac{8}{3\pi}}\left[2(0.25)^2 + 11\,(0.5)^2 + 2\,(1.0)^2 + 2\,(1.5)^2\right]^{1/2} = 2.82\,\text{dB}$$

And from equation 9-8:

$$\textit{Maximum PDL} = 3\,\sqrt{\frac{3\pi}{8}}\,2.82 = 9.2\ \ (\text{dB})$$

The induced power fluctuations from PDL and the effects of polarization-dependent gain (PDG) are transformed at optical amplifiers into OSNR fluctuations. The optical line amplifiers may not be able to compensate for the variation of attenuation originated from rapid variation of the state of polarization. Consequently, the overall variation of attenuation due to PDL appears as a penalty on the OSNR at the receiver end-point.

The resulting Maximum PDL figure of 9.2 dB is rather high. However, in this system the Maximum PDL value represents a peak-to-peak value with regard to all possible states of polarization. This means that, depending on the state of polarization we will have a variation of ±Maximum PDL/2 (±4.6 dB in this case) around the average value.

These power fluctuations may be too fast to be fully compensated by means of dynamic gain equalization.

II.4 Examples of the impact of cascaded ONEs on line system channel ripple

As discussed in clause 9.4, it is not possible to calculate the effect of multiple ONEs on end-to-end line system channel ripple unless the exact form of the filter function of all of the ONEs is known. To illustrate this, the effect of cascading eight Gaussian filters is compared with the effect of cascading eight flat-topped filters in two examples below.

Figure II.3 shows the insertion loss vs offset from the nominal DWDM grid frequency of eight Gaussian optical filters. Each of the filter shapes and centre frequencies is slightly different due to manufacturing tolerances and differences in temperature, etc. The average width of the eight filters at the –1 dB points is ±15.8 GHz and the average edge steepness at the –5 dB points is 0.28 dB/GHz.

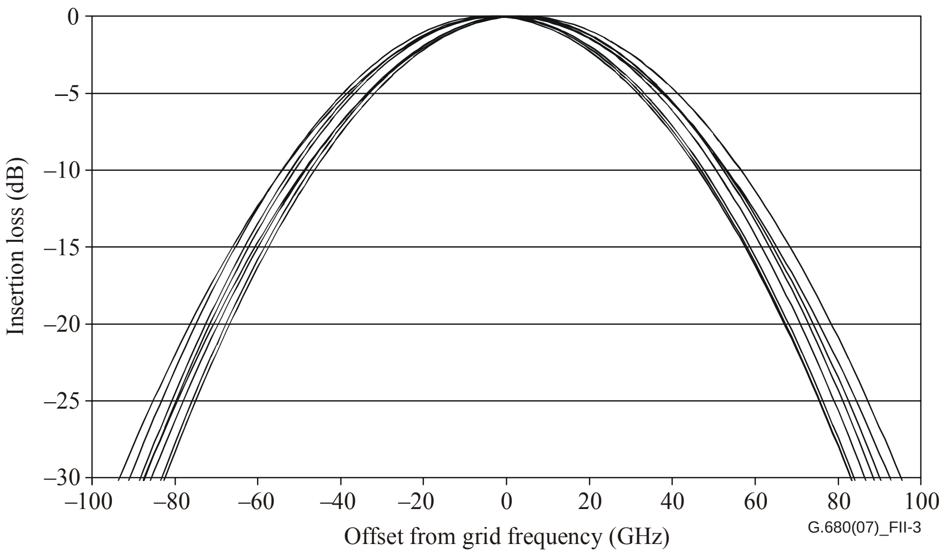

Figure II.3 – Superimposed filter shapes of eight Gaussian filters

When these eight filters are cascaded, the passband narrows considerably (by a factor of 2.9) and the edges of the combined filter function are much steeper as shown in Figure II.4. The width of the combined filter function at the –1 dB points is ±5.4 GHz and the average edge steepness at the –5-dB points is 0.8 dB/GHz.

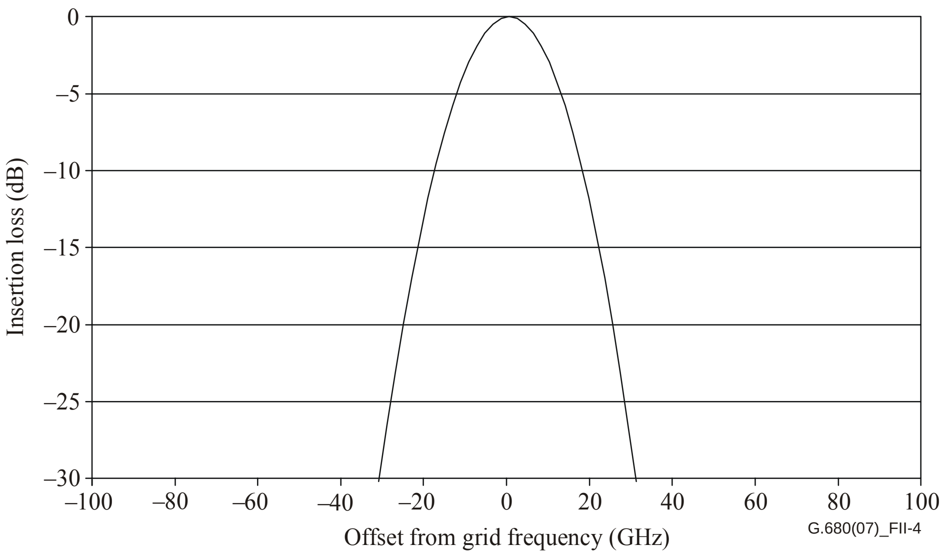

Figure II.4 – Resulting filter function of eight concatenated Gaussian filters

In contrast to this, Figure II.5 shows the insertion loss vs offset from the nominal DWDM grid frequency of eight flat-topped optical filters. As with the Gaussian filters, each of the filter shapes is slightly different due to manufacturing tolerances and differences in temperature, etc. The average width of the eight filters at the –1-dB points is ±39.4 GHz and the average edge steepness at the –5-dB points is 0.62 dB/GHz.

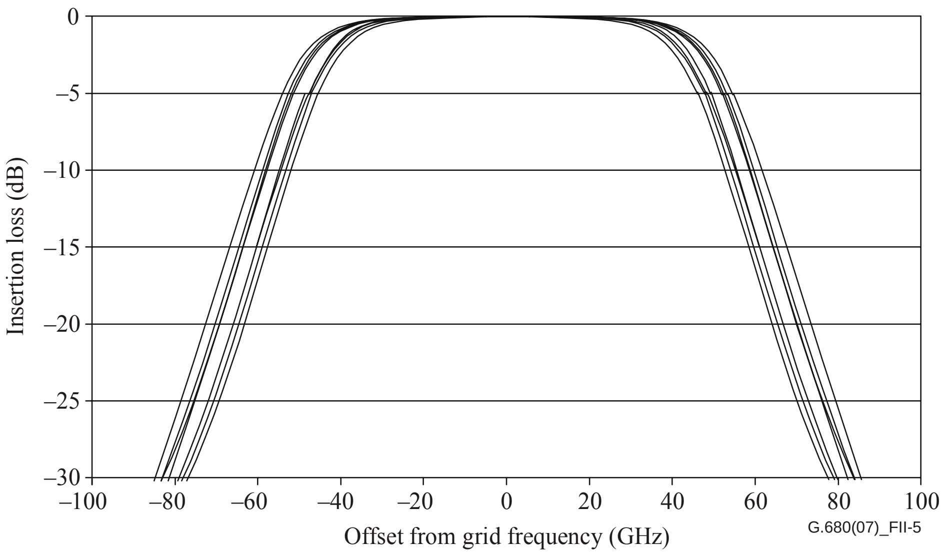

Figure II.5 – Superimposed filter shapes of eight flat-topped filters

When these eight flat-topped filters are cascaded, the passband narrows, but to a lesser extent than for the Gaussian filters (only by a factor of 1.77) and the edges of the combined filter function are 1.2 times steeper as shown in Figure II.6. The width of the combined filter function at the –1 dB points is ±22.2 GHz and the average edge steepness at the –5-dB points is 0.75 dB/GHz.

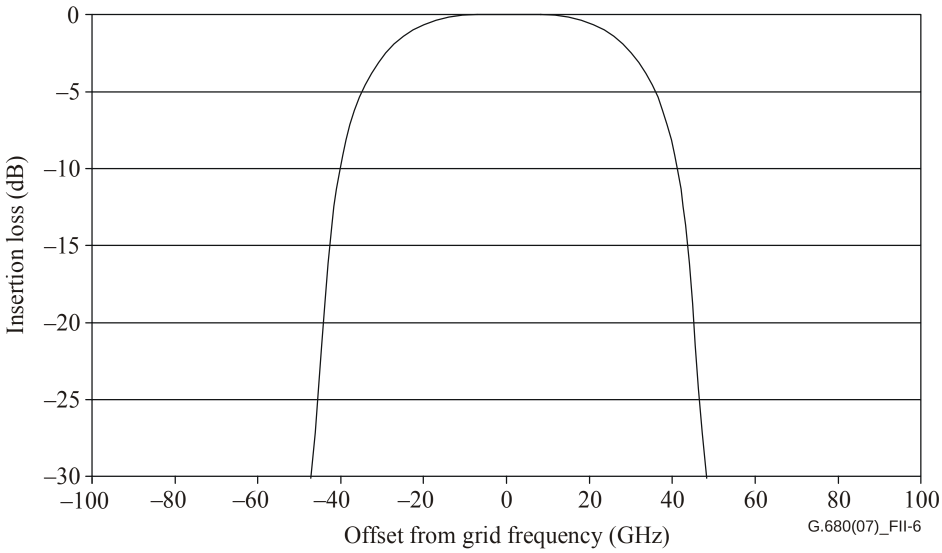

Figure II.6 – Resulting filter function of eight concatenated flat-topped filters

These examples have only considered how the end-to-end amplitude response of a path through an optical network depends on the filter functions of the individual ONEs. In order to avoid significant penalties due to traversing multiple ONEs it is also necessary that the end-to-end optical phase response is taken into account. This is for further study.

II.5 Example of the impact of cascaded ONEs on line system transients

As discussed in clause 9.5, this Recommendation currently does not enable the transient response of a cascade of optical amplifiers (in ONEs or line segments) to be determined (even when the exact nature of the stimulus is known), but confines itself to providing a suitable parameter set to describe the output transients due to a specified input stimulus.

The stimulus is characterized by the two following parameters:

– power change (dB);

– rate of change of power (dB/ms).

In this appendix, a reasonable range of values of these two parameters are given; however, these values may not represent the stimulus which cause the worst transient conditions.

II.5.1 Power change

The power change can be quantified as the ratio between the number of channels at the reference point after the channels are added or dropped and the number of channels at that reference point previously.

For the case when channels are added (as illustrated on the right side of Figure 9-1):

$$Power\,change = 10\log_{10}\left(\frac{A+U}{U}\right)$$

where:

A is the number of added channels

U is the number of undisturbed channels

For the case when channels are dropped (as illustrated on the left side of Figure 9-1):

$$Power\,change = 10\log_{10}\left(\frac{U}{D+U}\right)$$

where:

D is the number of dropped channels

U is the number of undisturbed channels

For example:

– adding 7 channels with one channel undisturbed gives a power change of +9 dB;

– dropping 7 channels with one channel undisturbed gives a power change of –9 dB;

– adding 31 channels with one channel undisturbed gives a power change of +15 dB;

– dropping 31 channels with one channel undisturbed gives a power change of –15 dB;

II.5.2 Rate of change of power

The power variation of the stimulus is not instantaneous, but it has a slope quantified by the parameter *rate of change of power*. A reasonable estimate of this quantity can be found from dividing the *power change* by the duration of the stimulus.

The duration of the stimulus can vary over a wide range because it is related to the various causes of the stimulus itself. Figure II.7 gives an indication of some typical stimulus durations from a variety of causes.

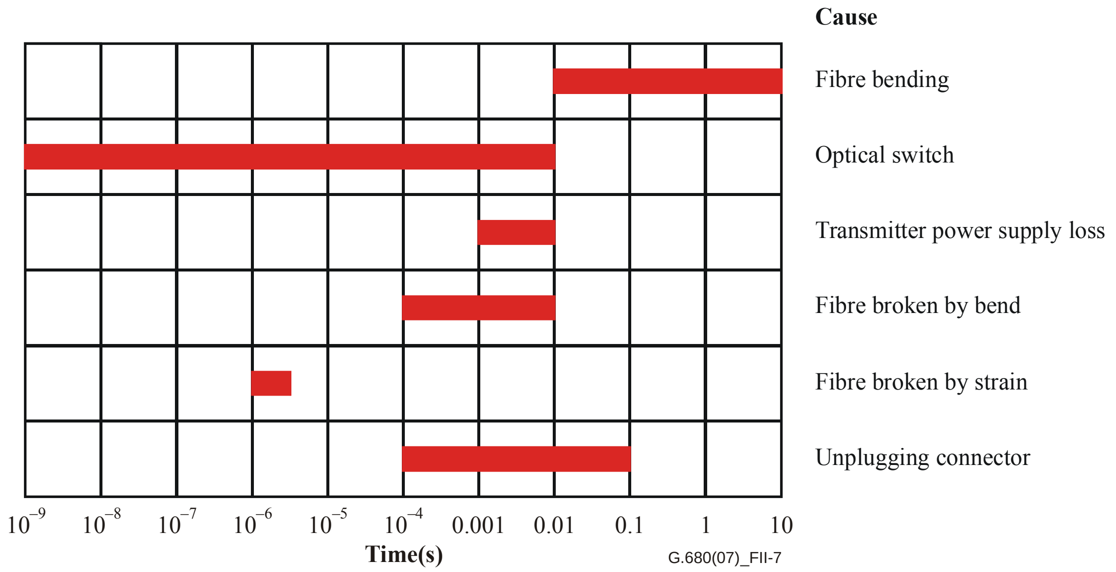

Figure II.7 – Possible stimulus duration

For the purpose of this Recommendation the stimulus duration can be assumed to be within 1 µs and 1 ms. Although the speeds of some optical switches can be much faster than 1 µs, by avoiding the use of such switches in the network it is possible to ensure that such rapid switching events do not occur due to network rearrangement. Consequently, the 1-µs stimulus that can be caused by a fibre broken by strain becomes the limiting value. On the other end of the scale there are many causes that generate power variations over timescales up to tens of seconds (and much longer than this for temperature and aging effects). However, for stimulus durations longer than about 1 ms, the combination of transient suppression in the amplifiers and the AGC capabilities in the receivers mean that they no longer need to be considered as transients.

II.5.3 Example transient response from a single amplifier

As noted in clause 9.5, if the number of channels passing through an EDFA is suddenly increased or decreased, then the optical power of the pumps of that amplifier will need to be increased or decreased in order to maintain a constant gain per channel. If this is not done, then large changes in amplifier gain can be seen as illustrated in Figure II.8 for + and –3 dB power change at the input of the amplifier (the same number of channels added and dropped as undisturbed). If, however, the amplifier includes suitable control of the pump power, the resulting transient on the undisturbed channels can be small as illustrated in Figure II.9.

Since the exact characteristics of the transient induced on the undisturbed channels is dependent on the particular implementation of the circuitry used to control the pump power of the EDFA, example transient responses from practical transient suppressed amplifiers are given in clauses II.5.3.1 and II.5.3.2.

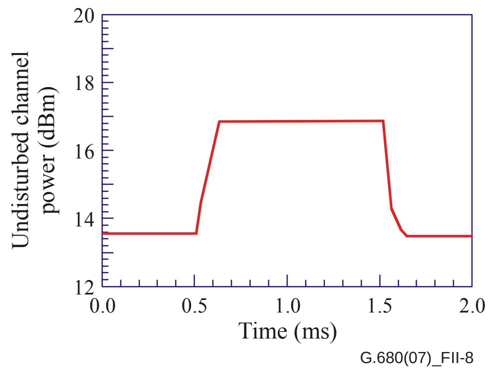

Figure II.8 – Output power of undisturbed channel with gain control off (constant pump power)

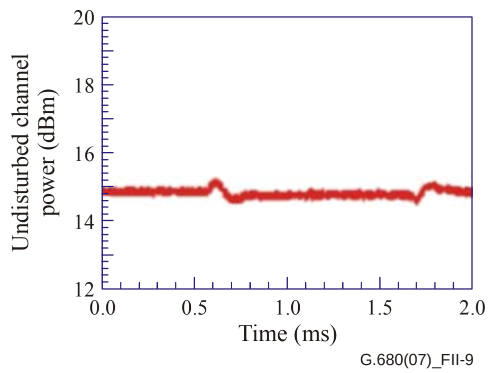

Figure II.9 – Output power of undisturbed channel with gain control on

II.5.3.1 Transient response of amplifier example A

The response of amplifier example A operating with 25 dB of gain to both add and drop stimuli of duration of 1 ms is given in Table II.6.

Table II.6 – Transient response of amplifier example A to a 1-ms stimulus

Stimulus		9 dB add	9 dB drop	15 dB add	15 dB drop
Total channels		8	8	32	32
Added/dropped channels		7	7	31	31
Undisturbed channels		1	1	1	1
Power change	dB	+9	–9	+15	–15
Stimulus duration	ms	1	1	1	1
Rate of change of power	dB/ms	+9	–9	+15	–15
Transient duration	ms	1.5	2.0	2.5	2.5
Transient gain increase	dB	0.5	0.8	2.5	2.5
Transient gain reduction	dB	0.5	0.5	2.5	2.5

II.5.3.2 Transient response of amplifier example B

The response of amplifier example B operating with 20 dB of gain to both add and drop stimuli of duration of 1 ms is given in Table II.7 and a duration of 1 µs in Table II.8.

Table II.7 – Transient response of amplifier example B to a 1-ms stimulus

Stimulus		10 dB add	10 dB drop	20 dB add	20 dB drop
Total channels		10	10	100	100
Added/dropped channels		9	9	99	99
Undisturbed channels		1	1	1	1
Power change	dB	+10	–10	+20	–20
Stimulus duration	ms	1	1	1	1
Rate of change of power	dB/ms	+10	–10	+20	–20
Transient duration	ms	2.0	2.0	3.0	3.0
Transient gain increase	dB	0.2	0.5	0.2	0.7
Transient gain reduction	dB	0.4	0.3	0.7	0.5

Table II.8 – Transient response of amplifier example B to a 1-µs stimulus

Stimulus		10 dB add	10 dB drop	20 dB add	20 dB drop
Total channels		10	10	100	100
Added/dropped channels		9	9	99	99
Undisturbed channels		1	1	1	1
Power change	dB	+10	–10	+20	–20
Stimulus duration	ms	0.001	0.001	0.001	0.001
Rate of change of power	dB/ms	+10'000	–10'000	+20'000	–20'000
Transient duration	ms	1.0	1.0	1.0	1.0
Transient gain increase	dB	1.0	3.0	1.0	5.0
Transient gain reduction	dB	2.0	1.0	3.0	1.0

II.6 Example of the impact of the channel uniformity of cascaded ONEs on line system performance

In order to illustrate the effect of the channel uniformity of multiple ONEs on line system performance, an example system is shown in Figure II.10.

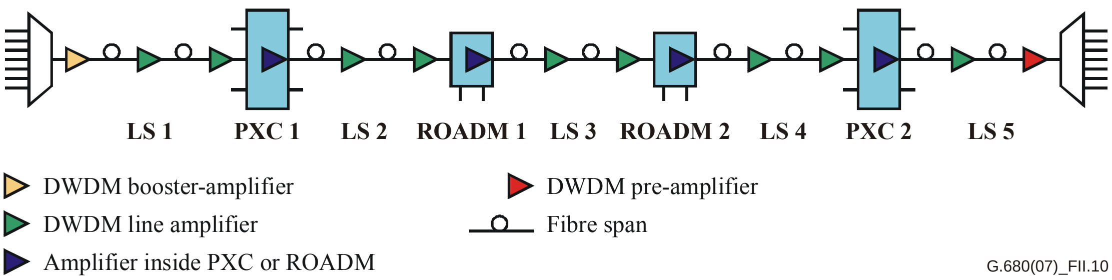

Figure II.10 – Configuration of channel uniformity example system

This example also assumes:

– The characteristics of the ROADMs are taken from the example found in Table I.3.

– The characteristics of the PXCs are taken from the example found in Table I.5.

– The channel uniformity of the line segments is 2 dB.

From Table I.3 the channel uniformity of the ROADMs is 2 dB and from Table I.5 the channel uniformity of the PXCs is 3 dB.

Applying equation 9-10 to this information gives:

End-to-end channel uniformity = 2 + 3 + 2 + 2 + 2 + 2 + 2 + 3 + 2 = 20 dB

The evolution of the worst case end-to-end channel uniformity for the configuration in Figure II.10 is shown in Table II.9

Table II.9 – Worst case end-to-end channel uniformity evolution

	LS 1	**PXC 1**	**LS 2**	**ROADM 1**	**LS 3**	**ROADM 2**	**LS 4**	**PXC 2**	**LS 5**
ONE channel uniformity (dB)	2	3	2	2	2	2	2	3	2
End-to-end channel uniformity (dB)	2	5	7	9	11	13	15	18	20

This level of end-to-end channel uniformity would almost certainly cause some of the channels of this example system to not achieve the required BER either due to excessive OSNR for the lowest power channels or due to non-linear effects associated with the high-power channels.

If some more detailed information about the ONEs is available, it is possible to make a more accurate estimation of the end-to-end channel uniformity than this worst-case value.

The additional information assumed in this example are:

– There are 8 DWDM channels labelled A to H.
– The 2-dB worst-case channel uniformity of the ROADMs is made up of a random part with a standard deviation of 0.15 dB and an average channel gain across many devices of –1.0, –0.56, –0.15, 0.0, 0.0, –0.15, –0.56 and –1.0 dB for channels A to H respectively.
– The 3-dB worst-case channel uniformity of the PXCs is made up of a random part with a standard deviation of 0.4 dB and an average channel gain across many devices of –0.5, –0.3, –0.1, 0.0, 0.0, –0.1, –0.3, and –0.5 dB for channels A to H respectively.
– The 2-dB worst-case channel uniformity of the line segments is made up of a random part with a standard deviation of 0.2 dB and an average channel gain across many line segments of –0.5, –0.1, 0.1, 0.0, –0.1, –0.2, –0.1 and 0.3 dB for channels A to H respectively.

Firstly, calculate the relative channel gains due to the non-random effects using equation 9-12 and then find the highest and lowest:

Channel A relative gain = –0.5 + –0.5 + –0.5 + –1.0 + –0.5 + –1.0 + –0.5 + –0.5 + –0.5 = –5.5 dB

Channel B relative gain = –0.1 + –0.3 + –0.1 + –0.56 + –0.1 + –0.56 + –0.1 + –0.3 + –0.1 = –2.22 dB

etc…

This gives relative channel gains of –5.5, –2.22, 0.0, 0.0, –0.5, –1.5, –2.22 and –1.5 dB for channels A to H respectively.

Secondly, the end-to-end standard deviation can be found by applying equation 9-11:

$$\sigma_e = \sqrt{\left(0.2^2 + 0.4^2 + 0.2^2 + 0.15^2 + 0.2^2 + 0.15^2 + 0.2^2 + 0.4^2 + 0.2^2\right)} = 0.75\,\text{dB}$$

Since the random variation applies to all of the channels, it is expected that the end-to-end relative channel gain for channel A will be less than –5.5 –3 × 0.75 = –7.75 dB for only ~1 in 1000 links.

Likewise, it is expected that the end-to-end relative channel gain for channel C will be more than $0.0 + 3 \times 0.75 = 2.25$ dB for only ~1 in 1000 links.

From this, the end-to-end channel uniformity can be estimated as 10 dB with only a small probability that this value will be exceeded in the actual link.

This value, while being much more likely to be acceptable than the value of 20 dB given by the worst-case calculation, is still high enough that some of the channels of this example system may not achieve the required BER either due to excessive OSNR for the lowest power channels or due to non-linear effects associated with the high power channels. If this is the case, then either ONEs with better performance than these example values must be used or the end-to-end channel uniformity must be improved by the addition of one or more dynamic channel equalizers as described in [ITU-T G.671].

Appendix III

Example application of this Recommendation

(This appendix does not form an integral part of this Recommendation)

One application of this Recommendation is to enable, at the moment of the activation/rerouting of an optical channel, the calculation of the overall degradation of the chosen route on the basis of the "degradation function" of each ONE involved and to evaluate whether the overall degradation is compatible with the error performance objectives at the O/E/O 3R end-point. If this check gives a positive answer, the optical channel is activated. If the check is negative, it will be necessary either to find another route or to insert a 3R regeneration point at a suitable place along the route. (See Figure III.1 for an example path.)

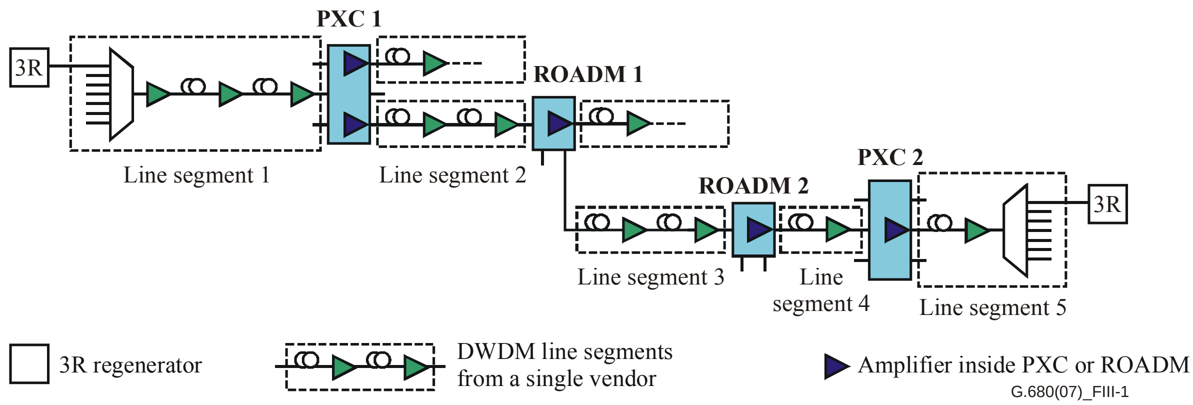

Figure III.1 – Example optical transmission system

All of the parameters considered in clause 9 have to be taken into account for the evaluation of the total degradation between O/E/O 3R end-points. For these parameters it is necessary to evaluate their total effect (accumulated effect) due to all of the cascaded ONEs inserted along the link.

In the present version of this Recommendation (Situation 1), there is the constraint that the calculation and the management of the overall degradation is possible only if the DWDM line segments are from the same vendor and all of the detailed parameters of the line segments, including any non-linear effects (which are outside the scope of this version of this Recommendation), are known.

III.1 Procedure

The sequence to be followed in the calculation of the overall degradation of an optical route should be the following:

i) The route of the optical channel must be completely defined, with all the ONEs which are involved;

ii) The values of the parameters of the transfer function of each ONE involved, as listed in the relevant tables of clause 8, must be obtained;

iii) The values of the parameters of the DWDM line segments including any non-linear effects must be available;

iv) as a consequence of the three steps above (but mainly step iii) the end-to-end performance calculation is performed in some cases by the line segment vendor, while in others the operator may be able to obtain sufficient information to perform the calculation;

v) the impact on line system performance of the combination of transfer parameters related to the cascaded ONEs inserted in the optical route together with the corresponding parameters from the DWDM line segments, is calculated following the guidelines given in clauses 9 and 10 and taking into account any non-linear effects.

III.2 An example of this procedure

Figure III.1 illustrates the desired route of one channel through an example DWDM network.

For item i of clause III.1, the signal from the transmitter on the left (part of the 3R regenerator) traverses, in turn:

– Line segment 1 which includes a multiplexer at the input;
– PXC1;
– Line segment 2;
– ROADM1 where it is one of a number of channels which exit on the drop port;
– Line segment 3;
– ROADM2 where it is exits on the output port;
– Line segment 4;
– PXC2;
– Line segment 5 which includes a de-multiplexer at the output.

Before arriving at the receiver of the 3R regenerator on the right.

For item ii of clause III.1, the parameters required for each ONE are:

– For PXC1 values for the parameters from Table 8-9;
– For ROADM1 values for the parameters from Table 8-6 relevant to the path from input to drop;
– For ROADM2 values for the parameters from Table 8-6 relevant to the path from input to output;
– For PXC2 values for the parameters from Table 8-9.

For item iii of clause III.1, the values of the parameters required to describe the performance of the five DWDM line segments (including the multiplexer within line segment 1 and the de-multiplexer within line segment 5) must be obtained. These are:

– for the multiplexer within line segment 1, values for the relevant parameters from Table 8-1 e.g., the loss, ripple, dispersion, DGD, PDL, channel uniformity, etc.
– for the amplifiers within line segments 1 to 5, values for the relevant parameters from both Tables 8-1 and 8-2 e.g., the gain, noise figure, DGD, etc.
– for all of the fibre spans within line segments 1 to 5, the values for the attenuation, chromatic dispersion and PMD and details of the channel power levels to allow for estimation of the non-linear penalties.
– for all of the dispersion compensating modules within line segments 1 to 5, values for the attenuation, chromatic dispersion and PMD.
– for the de-multiplexer within line segment 5, values for the relevant parameters from Table 8-1 e.g., the loss, ripple, dispersion, DGD, PDL, isolation, channel uniformity, etc.

NOTE – The exact details of the above information and how to use it to calculate the performance of the DWDM line segments is outside the scope of this version of this Recommendation.

For item iv of clause III.1, the availability of the above information determines who is able to perform the calculations. This may be the DWDM line segment vendor, the network operator or possibly a third party. This is discussed in more detail in Appendix IV.

For item v of clause III.1, all of the above information is brought together to allow the total degradation between O/E/O 3R end points for all of the required paths through the network to be evaluated. As described in clause 10, the overall optical budget for the systems considered in this Recommendation are defined in terms of OSNR, using equations 10-2 and 10-3.

For equation 10-2, which is:

$$\textit{Min OSNR} > \textit{Receiver OSNR tolerance} + \textit{Max optical path OSNR penalty}$$

the Receiver OSNR tolerance (defined in clause 10) is a parameter of the single channel receiver which must be obtained from the receiver supplier.

In order to illustrate this procedure, this example assumes a receiver compliant to application code DN100C-2A2(C)F in ITU-T Rec. G.698.2 which would have a Receiver OSNR tolerance of 16 dB when receiving a 10G NRZ signal with G.709 FEC enabled.

The Min OSNR in equation 10-2 is found from equation 10-3, which is:

$$\textit{Min OSNR} = \textit{OSNR} - \textit{OSNR reduction from channel uniformity} - \textit{OSNR reduction from PDL}$$

Since the parameters required to account for these factors in all of the elements in the end-to-end optical path are now available, they can be calculated as detailed in clause 9.6 for channel uniformity and in clause 9.3.2 for PDL.

As detailed in clause 10, the maximum optical path OSNR penalty must be calculated taking into account:

– The worst-case ripple (clause 9.4) and ensure that the end-to-end filter function when combined with the worst-case transmitter spectral excursion does not result in excessive path penalty.
– The worst-case PMD (clause 9.3.1) and ensure that the end-to-end PMD taken together with the acceptable outage probability does not exceed the DGD tolerance of the receiver.
– The worst-case residual dispersion (clause 9.2) and ensure that this does not exceed the residual dispersion tolerance of the transmitters.
– The non-linear effects in the DWDM line segments which are outside the scope of this version of this Recommendation (Situation 1).

To continue to use the application code DN100C-2A2(C)F in ITU-T Rec. G.698.2 to illustrate this process, the maximum optical path OSNR penalty of a black link compliant to that code would be 5 dB.

This results in equation 10-2 becoming:

$$\textit{Min OSNR} > 16 + 5 = 21 \text{ dB}$$

Therefore, as long as the minimum OSNR calculated from equation 10-3 for each path through the network is larger than this value, the required BER should be met.

Appendix IV

The users of this Recommendation

(This appendix does not form an integral part of this Recommendation)

IV.1 Introduction

In Appendix III, an example is given of how this Recommendation may be used for a certain task. Here, we try to define the potential users of this Recommendation and to describe their different roles in that use. For this version of the Recommendation the situation is restricted to Situation 1 as described in Figure 1-1. However, it is expected that a future revision will cover Situation 2 as described in Figure 1-2.

Only information exchange is described here. The legal and commercial relationship between the partners involved is outside of the scope of this Recommendation.

IV.2 The actors in the use of this Recommendation

Several actors in the use of this Recommendation can be identified:

– the network operator, who plans, orders and runs the system (who offers services and accounts for them, monitors the performance of the system and predicts new demands of his clients);

– the system designer (which might be a general system supplier, the network operator itself or both in close cooperation), who collects information from other partners and uses it;

– the subsystem vendors (the vendor of the DWDM line segments including fibres and optical amplifiers, vendors of OADMs and vendors of PXCs);

– the vendor of the terminal equipment (OM, OD, transponders, VOAs, booster and preamplifiers, ADCs), who has to generate and to detect a signal which is suited for transmission over the optical path the subsystem impairments of which are described in this Recommendation. Some of the equipment quoted in this list (e.g., OM, OD, optical amplifiers, VOAs, ADCs) are usually the components/subsystems of the DWDM line segments, but can also be part of the terminal equipment;

– the vendor of the control and management system (equipment and software to remotely control the power levels at various reference points, to switch the OADMs and the PXCs, to tune the ADCs and PMDCs as well as to configure the transponders, to monitor the performance of the network and its services, and to detect faults and to localize and to alarm them) which is necessary to run the system. For further details, see [b-ITU-T M.3010] "Principles for a telecommunications management network" and other Recommendations of this series.

Each of them can play different roles here.

IV.3 Example of the activities of the actors

One example of the possible activities of these actors is given in the following:

An operator plans to realize an all-optical network (AON) in all or in a part of its own territory. The operator plans to install gradually over time some DWDM line segments, OADMs, PXCs and terminal equipment to be connected together as soon as they are deployed. In order to define the characteristics of all of this equipment, the operator characterizes the length of the optical channels routed through its AON and the number and type of the nodes to be involved in these paths.

The network operator then asks a vendor of DWDM line segments for information necessary for the evaluation of all of the required paths through the network.

The DWDM line segment vendor receives directly from the OADM and the PXC vendors, or through the operator, the values of the parameters which characterize the various OADMs and PXCs involved in the optical path and their number.

The system designer evaluates the feasibility of all of the required optical paths on the basis of the received data on the OADMs, on the PXCs, on the DWDM line segments (including non-linear effects), on the terminal equipment and of the procedures indicated in this Recommendation.

If there are technical difficulties in satisfying the above requirements, the operator can change the requirements (e.g., reducing the extension of the AON by inserting 3R regenerators or specifying higher performance ONEs, etc.).

If the extra cost to be paid today for the deployment of the ONEs designed for a future AON (i.e., over dimensioned) is judged too high, it could be possible to reduce this cost by reducing the extension of the AON. Of course, this choice will reduce the percentage of the channels to be realized all optically.

The vendor of the control and management system must be involved if it is required that the network with its new elements will be integrated into an existing control and management system or, of course, if a new control and management system is to be installed.

In the building phase, the DWDM line segments, the OADMs, the PXCs and the terminal equipment may be deployed step by step. Here, this Recommendation may serve to support the network operator in the decision to activate a specific optical channel after verification that the end-to-end impairments are low enough to support the required end of life BER.

NOTE – It is also possible that the operator may charge the DWDM line segment vendor to perform these calculations.

In the running phase, the network operator is free to activate any of the previously defined paths through the network. This freedom is very important for the management of double-fault situations (e.g., for the restoration of an AON in case of a double-fault situation).

As a result of running the system, the network operator may decide to upgrade the system. Since this is a new planning process, this Recommendation may be re-applied:

i) In the case of addition of new nodes and of new connections between them, the percentage of the all optical channels may not vary so much, if this addition is made inside the area of the AON;

ii) If the operator wishes to have two different vendors for the DWDM line segments, it is possible to divide the area of the AON in two parts and to plan the insertion of 3R regenerators at the boundaries (in Situation 1). It is expected that a future revision of this Recommendation will allow more than one DWDM line segment vendor within a single AON without requiring the additional 3R regenerators (Situation 2), therefore providing a more cost-effective solution.

Bibliography

[b-ITU-T G.Sup39] ITU-T G-series Supplement 39 (2006), *Optical system design and engineering considerations.*

[b-ITU-T M.3010] ITU-T Recommendation M.3010 (2000), *Principles for a telecommunications management network.*

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