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

Transmission media characteristics – Characteristics of optical components and subsystems

Longitudinally compatible intra-domain DWDM applications

ITU-T Recommendation G.696.1

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ITU-T Recommendation G.696.1

Longitudinally compatible intra-domain DWDM applications

Summary

This Recommendation provides physical layer specifications for intra-domain (IaD) DWDM optical networking applications. Longitudinally compatible applications inside a single administrative domain are described for point-to-point, multichannel line systems with or without line amplifiers. The application codes in this Recommendation provide a set of categories for DWDM transmission systems and fibre links. The primary purpose is to enable multiple vendors to design DWDM transmission equipment for fibre links that are compliant with this Recommendation.

Source

ITU-T Recommendation G.696.1 was approved on 14 July 2005 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

FOREWORD

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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.

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Longitudinally compatible intra-domain DWDM applications

1 Scope

This Recommendation provides physical layer specifications for intra-domain (IaD) DWDM optical networking applications. These specifications are provided for point-to-point, multichannel line systems with or without line amplifiers. The goal is to enable longitudinally compatible applications inside an administrative domain. The primary purpose is to enable multiple vendors to provide transmission equipment for fibre links that are compliant with this Recommendation.

In order to provide a framework for IaD application specifications, this Recommendation includes a generic reference model for the physical layer applications. The specifications are organized according to application codes, which take into account parameters such as operating wavelength ranges of the optical amplifiers, combinations of channel counts, client classes, span distances, fibre types and system configurations.

This initial Recommendation focuses on IaD applications without intervening optical switching elements. It is expected that future versions and/or other new Recommendations may address more complex physical layer configurations and/or support a higher level of compatibility. For these applications, different parameters beyond those specified for a point-to-point configuration may be required.

This Recommendation presumes that the optical tributary signals transported within Optical Channels are digital rather than analogue. Specifications for systems enabling transport of analogue optical tributary signals are for further study.

2 References

2.1 Normative 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 Recommendation G.650.2 (2005), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

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

– ITU-T Recommendation G.653 (2003), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.654 (2004), *Characteristics of a cut-off shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.655 (2003), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.

– ITU-T Recommendation G.663 (2000), *Application related aspects of optical amplifier devices and subsystems* plus Amendment 1 (2003), *Amendments to Appendix II*.

– ITU-T Recommendation G.664 (2003), *Optical safety procedures and requirements for optical transport systems* plus Amendment 1 (2005).

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

– ITU-T Recommendation G.691 (2003), *Optical interfaces for single-channel STM-64 and other SDH systems with optical amplifiers* plus Amendment 1 (2005).

– ITU-T Recommendation G.707/Y.1322 (2003), *Network node interface for the synchronous digital hierarchy (SDH)* plus Amendment 1 (2004) and Corrigendum 1 (2004).

– ITU-T Recommendation G.709/Y.1331 (2003), *Interfaces for the Optical Transport Network (OTN)* plus Amendment 1 (2003).

– ITU-T Recommendation G.872 (2001), *Architecture of optical transport networks* plus Amendment 1 (2003) and Corrigendum 1 (2005).

– ITU-T Recommendation G.957 (1999), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy* plus Amendment 1 (2003) and Amendment 2 (2005).

– ITU-T Recommendation G.959.1 (2003), *Optical transport network physical layer interfaces*.

– IEC 60825-1 (2001), *Safety of laser products – Part 1: Equipment classification, requirements and user's guide*.

– IEC 60825-2 (2005), *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*.

– IEC/TR 61292-4 (2004) *Optical amplifiers – Part 4: Maximum permissible optical power for the damage-free and safe use of optical amplifiers, including Raman amplifiers.*

2.2 Informative references

– ITU-T Recommendation G.975.1 (2004), *Forward error correction for high bit-rate DWDM submarine systems.*

– ITU-T G-series Recommendations – Supplement 39 (2003), *Optical system design and engineering considerations*.

3 Terms and definitions

3.1 Definitions

This Recommendation defines the following terms:

3.1.1 client class: The client class refers to a class of bit rates of the client signal of a single optical tributary signal that is placed within an optical channel for transport across the optical network. In the context of this Recommendation, the client bit rate is the bit rate of a continuous digital signal before any additional FEC bytes have been added. In the case of a signal in accordance with ITU-T Rec. G.707/Y.1322, this would be the rate of the ODUk.

3.1.2 client class 1.25G: Applies to a continuous digital signal with a client bit rate from nominally 622 Mbit/s to nominally 1.25 Gbit/s. The client class 1.25G includes a signal with STM-4 bit rate according to ITU-T Rec. G.707/Y.1322.

3.1.3 client class 2.5G: Applies to a continuous digital signal with a client bit rate from nominally 622 Mbit/s to nominally 2.5 Gbit/s. The client class 2.5G includes a signal with STM-16 bit rate according to ITU-T Rec. G.707/Y.1322 and ODU1 bit rate according to ITU-T Rec. G.709/Y.1331.

3.1.4 client class 10G: Applies to a continuous digital signal with a client bit rate from nominally 2.4 Gbit/s to nominally 10.5 Gbit/s. The client class 10G includes a signal with STM-64 bit rate according to ITU-T Rec. G.707/Y.1322 and ODU2 bit rate according to ITU-T Rec. G.709/Y.1331.

3.1.5 client class 40G: Applies to a continuous digital signal with a client bit rate from nominally 9.9 Gbit/s to nominally 42 Gbit/s. The client class 40G includes a signal with STM-256 bit rate according to ITU-T Rec. G.707/Y.1322 and ODU3 bit rate according to ITU-T Rec. G.709/Y.1331.

3.2 Terms defined in other Recommendations

This Recommendation uses the following terms defined in ITU-T Rec. G.872:

– Intra-domain interface (IaDI);

– 3R regeneration.

This Recommendation uses the following term defined in ITU-T Rec. G.709/Y.1331:

– Optical channel data unit (ODUk).

This Recommendation uses the following term defined in ITU-T Rec. G.959.1:

– Optical tributary signal.

4 Abbreviations

This Recommendation uses the following abbreviations:

3R (Regeneration) Re-amplification, Reshaping and Retiming

ASE Amplified Spontaneous Emission

BER Bit Error Ratio

DCM Dispersion Compensation Module

DEMUX Demultiplexer

DGD Differential Group Delay

DRA Distributed Raman Amplification

DWDM Dense WDM

EDFA Erbium Doped Fibre Amplifier

FEC Forward Error Correction

FWM Four-Wave Mixing

IaD Intra-Domain

IaDI Intra-Domain Interface

MPI Main Path Interface

MUX Multiplexer

NCG Net Coding Gain

NRZ Non-Return to Zero

OA Optical Amplifier

ODUk Optical channel Data Unit (k = 1, 2 or 3)

OPM	Optical Power Monitor
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-to-Noise Ratio
PDG	Polarization-Dependent Gain
PDL	Polarization-Dependent Loss
PMD	Polarization Mode Dispersion
PMD_Q	Statistical parameter for link PMD
RZ	Return to Zero
SPM	Self-Phase Modulation
VOA	Variable Optical Attenuator
WDM	Wavelength Division Multiplexing
XPM	Cross-Phase Modulation

5 Classification of optical interfaces

5.1 Applications

This Recommendation addresses longitudinally compatible Intra-Domain DWDM applications with or without optical line amplifiers. Different line amplifier types may be used, in particular discrete line amplifiers as described in ITU-T Rec. G.663, or Raman amplifiers according to ITU-T Rec. G.665.

5.2 Reference configurations

For the purpose of this Recommendation, the relevant reference points applicable to the Intra-Domain DWDM Interface applications are shown in Figure 5-1.

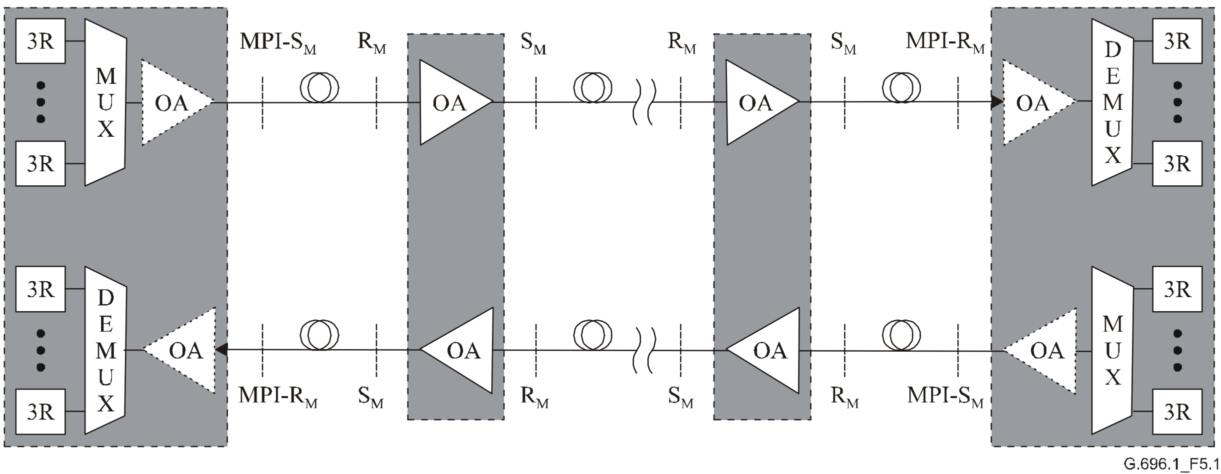

Figure 5-1/G.696.1 – Reference configuration for a multi-span DWDM system

The reference points in Figure 5-1 are defined as follows, using the same nomenclature as in ITU-T Rec. G.959.1:

– 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;

– S_M is a reference point just after the line multichannel OA output optical connector;

– R_M is a reference point on the optical fibre just before the line multichannel OA input optical connector.

5.3 Nomenclature

The application code notation is constructed as follows:

n.B-xWF(s)

where:

n is the maximum number of channels supported by the application code,

B indicates the client class:

– 1.25G indicating a client bit rate in the range from 622 Mbit/s to 1.25 Gbit/s;

– 2.5G indicating a client bit rate in the range from 622 Mbit/s to 2.5 Gbit/s;

– 10G indicating a client bit rate in the range from 2.4 Gbit/s to 10.5 Gbit/s;

– 40G indicating a client bit rate in the range from 9.9 Gbit/s to 42 Gbit/s.

x is the number of spans within the application code,

W is a letter indicating the span attenuation, such as
S indicating short-haul (up to 11 dB span attenuation),
L indicating long-haul (up to 22 dB span attenuation),
V indicating very long-haul (up to 33 dB span attenuation),

F is the (fully detailed) fibre type, such as G.652.A, … G.652.D denoted by "652A" … "652D" in the application code, respectively,

s indicates the operating wavelength range in terms of spectral bands (see ITU-T Supplement G.39):

s	Descriptor	Range (nm)
O	Original	1260 to 1360
E	Extended	1360 to 1460
S	Short wavelength	1460 to 1530
C	Conventional	1530 to 1565
L	Long wavelength	1565 to 1625

If more than one spectral band is used, then s becomes the band letters separated by "+" e.g., for an application requiring the use of both of the C and L bands, s would be "C+L". In cases where more than one spectral band is used, the order of letters used is lower wavelengths to higher wavelengths.

In case of a Raman amplified DWDM transmission system, a letter "R" shall be added at the end of the application code which is then written as:

n.B-xWF(s)R

An example of specific applications could look like this:

40.10G-20L652A(C)R

This application indicates a 40-channel system with signals of the 10G payload class, 20 long-haul spans of G.652A fibre which are suitable for use with Raman amplifiers. The C-band is used as the operating wavelength range.

6 Longitudinal compatibility

The applications covered by this Recommendation are longitudinally compatible according to the definition given in ITU-T Supplement G.39.

7 Parameters

The application codes used in this Recommendation (n.B-xWF(s)) consist of two separable sections. The first part "n.B" relates to the optical transmission system and the second part "xWF(s)" relates to the fibre infrastructure.

Since this Recommendation covers longitudinally compatible systems, the parameters contained in Table 7-1 relate to the fibre infrastructure only, except where the system-related part of the application code affects the fibre requirements.

Table 7-1/G.696.1 – Fibre parameters for intra-domain DWDM applications

Parameter	Clause
Maximum attenuation per span	7.1
Minimum attenuation per span	7.1
Fibre type	7.2
Operating wavelength range	7.3
Minimum chromatic dispersion per span	7.4
Maximum chromatic dispersion per span	7.4
Minimum local chromatic dispersion coefficient	7.5
Maximum chromatic dispersion deviation	7.6
Maximum differential group delay	7.7
Minimum optical return loss at MPI-S_M or S_M	7.8
Maximum discrete reflectance between MPI-S_M and MPI-R_M	7.9

7.1 Maximum and minimum attenuation per span

The maximum and minimum span attenuations are given in Table 7-2.

Table 7-2/G.696.1 – Maximum and minimum span attenuations

Parameter	Units	Value of "W" in application code		
		S	L	V
Maximum attenuation per span	dB	11	22	33
Minimum attenuation per span	dB	ffs	11	22

7.2 Fibre type

This Recommendation covers all of the fibre types in the ITU-T G.65x series of Recommendations. This currently includes the types given in Table 7-3.

Table 7-3/G.696.1 – Fibre types

G.652.A	G.653.A	G.654.A	G.655.A	G.656
G.652.B	G.653.B	G.654.B	G.655.B	
G.652.C		G.654.C	G.655.C	
G.652.D				

7.3 Operating wavelength range

The operating wavelength range consists of one or more of the wavelength bands as defined in ITU-T Supplement G.39. See Table 7-4.

Table 7-4/G.696.1 – Wavelength ranges

s	Descriptor	Range (nm)
O	Original	1260 to 1360
E	Extended	1360 to 1460
S	Short wavelength	1460 to 1530
C	Conventional	1530 to 1565
L	Long wavelength	1565 to 1625

7.4 Minimum and maximum chromatic dispersion per span

The minimum and maximum chromatic dispersion per span (excluding any dispersion compensation) can either be calculated by using standardized fibre parameters (from the G.65x-series) or it can be measured. For 40G systems and for 10G systems with many spans, the measurement is often the more practical choice.

A calculation of the minimum and maximum chromatic dispersion per span can be carried out by taking fibre parameters from Recommendations in the G.65x series, plus additional parameters used in this Recommendation. In detail, the calculation is then done as follows: The maximum chromatic dispersion per span, $CD_{\max}^{(span)}$, is given by:

$$CD_{\max}^{(span)} = D_{\max}(s) \cdot L_{\max}^{(span)}$$

where:

$$L_{\max}^{(span)} = \frac{A_{\max}(W)}{\alpha(s)}$$

is the maximum span length with the maximum span attenuation $A_{\max}$ (W) defined by the letter "W" (see Table 7-2), and the attenuation coefficient $\alpha(s)$ in the operating wavelength range "s" (see 5.3) where $\alpha(s)$ is the "typical link value" in the ITU-T G.65x series of Recommendations. The maximum chromatic dispersion coefficient in the operating wavelength range "s" is denoted as $D_{\max}(s)$.

Similarly, the minimum chromatic dispersion per span, $CD_{\min}^{(span)}$, is given by:

$$CD_{\min}^{(span)} = D_{\min}(s) \cdot L_{\min}^{(span)}$$

where:

$$L_{\min}^{(span)} = \frac{A_{\min}(W)}{\alpha(s)}$$

is the minimum span length with the minimum span attenuation A_{max} (W) defined by the letter "W" (see Table 7-2), and the attenuation coefficient $\alpha(s)$ in the operating wavelength range "s" (see 5.3) where $\alpha(s)$ is the "typical link value" in the ITU-T G.65x series of Recommendations. The minimum chromatic dispersion coefficient in the operating wavelength range "s" is denoted as $D_{min}(s)$.

Chromatic dispersion coefficients can be found for any fibre type in the ITU-T G.65x series of Recommendations series using there the "link attributes". Maximum and minimum span attenuations are defined in Table 7-2.

7.5 Minimum local chromatic dispersion coefficient

When considering the performance of individual channels in a multi-span transmission system, the end-to-end residual chromatic dispersion (including compensation) must be held within strict limits to allow acceptable system operation.

For acceptable operation of DWDM transmission systems over long distances with small channel spacing (e.g., 100 GHz), however, there is also a requirement for the local dispersion coefficient of the transmission fibre to have a minimum value in order to avoid non-linear effects such as four wave mixing (FWM) and cross-phase modulation (XPM).

The value of local chromatic dispersion coefficient required to avoid significant penalties due to these effects depends on many factors of the transmission system design such as the channel spacing, power level, link length, etc. and is, therefore, outside the scope of this Recommendation.

Further details of these non-linear effects are given in ITU-T Rec. G.663 and in ITU-T Supplement G.39, and some methods of mitigating them are discussed in clause I.3.

7.6 Maximum chromatic dispersion deviation

The requirements for maximum chromatic dispersion deviation are for further study.

7.7 Maximum differential group delay

The maximum differential group delay (DGD) applies to the whole link between a transmitter (shown as "3R" connected to a MUX in Figure 5-1) and the corresponding receiver ("3R" connected to the DEMUX in Figure 5-1).

The equation below can be used to calculate the maximum DGD of a link (containing multiple components and fibre sections) with a defined probability of being exceeded.

$$DGD\max_{link} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2}$$

where:

$DGD\max_{link}$ is the maximum link DGD (ps)

$DGD\max_F$ is the maximum concatenated optical fibre cable DGD (ps)

S is Maxwell adjustment factor (see Table 7-5)

PMD_{Ci} is PMD value of the ith 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 7-5.

Table 7-5/G.696.1 – 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}		

Further details can be found in ITU-T Recs G.650.2 and G.691. The value of $DGD\max_F$ (the maximum DGD due to the fibre part) can either be measured or, alternatively, an upper limit can be calculated for a given fibre length using the PMD_Q coefficient in the corresponding fibre Recommendation.

The DGD limits for the entire link are given in Table 7-6 for NRZ systems and Table 7-7 for RZ.

Table 7-6/G.696.1 – Maximum link differential group delay for NRZ

Client class	Units	Value
1.25G	ps	240
2.5G	ps	120
10G	ps	30
40G	ps	7.5

Table 7-7/G.696.1 – Maximum link differential group delay for RZ

Client class	Units	Value
1.25G	ps	ffs
2.5G	ps	ffs
10G	ps	ffs
40G	ps	ffs

7.8 Minimum optical return loss at MPI-S_M or S_M

Reflections are caused by refractive index discontinuities along the optical path. If not controlled, they can degrade system performance through their disturbing effect on the operation of the optical source or amplifier, or through multiple reflections which lead to interferometric noise at the receiver. Reflections from the optical path are controlled by specifying:

– the minimum optical return loss of the cable plant at the source reference point (e.g., MPI-S_M, S_M), including any connectors; and

– the maximum discrete reflectance between source reference points (e.g., MPI-S_M, S_M) and receive reference points (e.g., MPI-R_M, R_M).

Reflectance denotes the reflection from any single discrete reflection point, whereas the optical return loss is the ratio of the incident optical power to the total returned optical power from the entire fibre, including both discrete reflections and distributed backscattering such as Rayleigh scattering.

Measurement methods for reflections are described in Appendix I/G.957. For the purpose of reflectance and return loss measurements, points MPI-S and MPI-R are assumed to coincide with the endface of each connector plug. It is recognized that this does not include the actual reflection performance of the respective connectors in the operational system. These reflections are assumed to have the nominal value of reflection for the specific type of connectors used.

The minimum optical return loss of the cable plant at MPI-S_M or S_M is limited to –24 dB.

7.9 Maximum discrete reflectance between MPI-S_M and MPI-R_M

Optical reflectance is defined to be the ratio of the reflected optical power present at a point, to the optical power incident to that point. Control of reflections is discussed extensively in ITU-T Rec. G.957. The maximum number of connectors or other discrete reflection points which may be included in the optical path (e.g., for distribution frames, or WDM components), must be such as to allow the specified overall optical return loss to be achieved. If this cannot be done using connectors meeting the maximum discrete reflections cited here, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It may also be necessary to limit the number of connectors or to use connectors having improved reflectance performance in order to avoid unacceptable impairments due to multiple reflections.

The maximum discrete reflectance between MPI-S_M and MPI-R_M is limited to –27 dB.

8 Optical safety considerations

While this Recommendation relates to the fibre infrastructure and does not specify the characteristics of the optical transmission systems operating over it, such systems may well operate at relatively high optical power levels. Information on optical safety considerations can be found in ITU-T Rec. G.664, IEC 60825-1, IEC 60825-2 and IEC/TR 61292-4.

Appendix I

Theoretical limits and design considerations for DWDM systems

This appendix presents some physical and technology limitations to the achievable link distances of Intra-Domain DWDM optical transmission systems.

In clause I.1, the fundamental limits due to ASE noise and PMD are discussed. This is followed in clause I.2 with a discussion of other effects that limit the distances in practical systems and in clause I.3, techniques to mitigate these effects are described. Finally, in clause I.4, an example of the typical performance of currently available technology is given.

I.1 Enabling technologies and their limits

In this clause some of the fundamental constraints for the technological feasibility of DWDM applications are indicated.

It is assumed that the link optical attenuation is compensated for with optical amplifiers and the chromatic dispersion is compensated for with chromatic dispersion compensators.

ASE noise and PMD are the most important impairments that limit the capacity and transmission distance of DWDM applications.

The discussion in clause I.1 refers to NRZ line coding since this is commonly used in DWDM applications. Other line codings may give different results and might be more suitable in some cases (some alternatives to NRZ are discussed in clause I.3).

I.1.1 ASE noise

The influence of ASE noise is essentially characterized by OSNR. As shown in ITU-T Supplement G.39, the OSNR of a multichannel x span reference system with a booster amplifier, x–1 line amplifiers and a pre-amplifier is given by:

$$OSNR = P_{out} - L - NF_{eff} - 10 \cdot \log\left(x + \frac{10^{\frac{G_{BA}}{10}}}{10^{\frac{L}{10}}} \right) - 10 \cdot \log\left[h \cdot \nu \cdot \nu_r \right] \qquad \text{(I-1)}$$

P_{out} is the output power (per channel) of the booster and line amplifiers in dBm, L is the span loss in dB (which is assumed to be equal to the gain G_{LA} of the line amplifiers), G_{BA} is the gain of the optical booster amplifier in dB, NF_{eff} is the noise figure of the optical amplifier in dB, h is Planck's constant (in mJ*s to be consistent with P_{out} in dBm), ν is the optical frequency in Hz, ν_r is the reference bandwidth in Hz, x–1 is the total number of line amplifiers.

Equation I-1 takes into account the shot noise and the signal-spontaneous beat noise as the most dominant noise contributions. Other noise contributions might be considered in some cases.

This equation indicates that the ASE noise is accumulated from all x + 1 amplifiers.

For this reference system, the following main assumptions are made:

– All optical amplifiers in the chain including booster and pre-amplifier have the same noise figure.

– The losses (per channel) of all spans are equal.

– The output powers (per channel) of the booster and line amps are the same.

For example, assuming the optical channel output power $P_{out} = 3$ dBm, the noise figure $NF_{eff} = 6.5$ dB, the reference bandwidth $\nu_r = 0.1$ nm and the span loss L = 22 dB we get the solid curve shown in Figure I.1.

For a 10 Gbit/s data rate, and assuming an OSNR limitation of 25 dB for a BER of 10^{-12} without FEC, we get a theoretical limiting distance of 5 spans.

If we assume the use of G.709/Y.1331 FEC with a net coding gain (NCG) of 5.6 dB, the limiting OSNR becomes 19.4 dB which is reached at 20 spans.

Using stronger FEC, e.g., one of the schemes found in Appendix I/G.975.1, a net coding gain (NCG) of around 8 dB is feasible and the limiting OSNR becomes 17 dB which is reached at 35 spans.

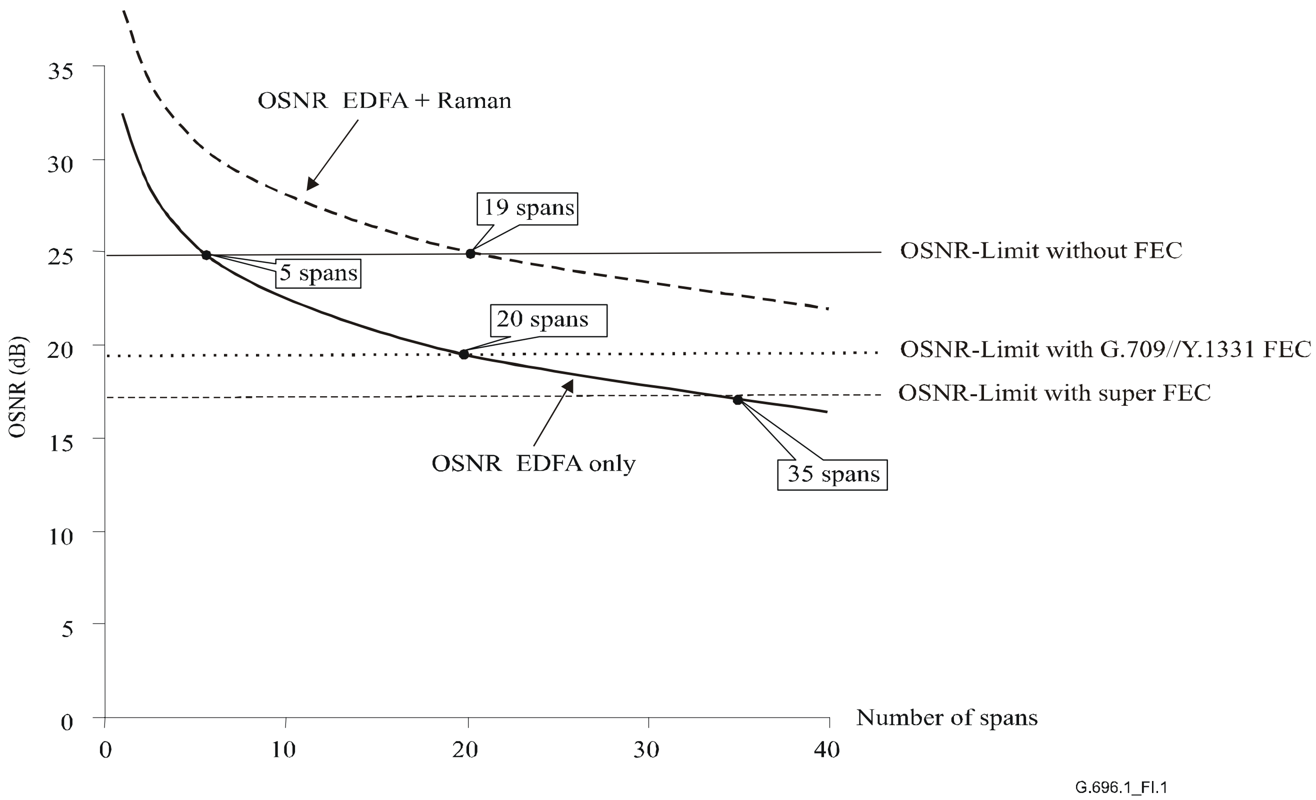

Figure I.1/G.696.1 – OSNR limits for a reference system, OSNR as a function of span number with and without Raman amplification

Distributed Raman Amplification (DRA) is a further option to extend transmission distance. The OSNR improvement factor expected by DRA in backward pumping configuration can be calculated by the effective noise figure (*NF_{eff}*) which can be expressed by Equation I-2 [1].

$$NF_{eff} = 10 \cdot \log\left(\left(NF'_{LA} + \frac{P_{ASE,Raman}}{h \cdot \nu \cdot \nu_r}\right) \cdot \frac{1}{G'_{Raman}}\right) \tag{I-2}$$

where NF'_{LA} is the linear noise figure of the discrete line amplifier, G'_{Raman} is the linear gain of DRA, $P_{ASE,Raman}$ is the ASE power resulting from DRA, ν_r is the reference bandwidth. The equation $NF_{LA} = 10 \cdot \log(NF'_{LA})$ holds where NF_{LA} is the noise figure of the discrete line amplifier in dB.

$P_{ASE,Raman}$ and $G_{Raman} = 10 \log \cdot (G'_{Raman})$ can be estimated analytically [2].

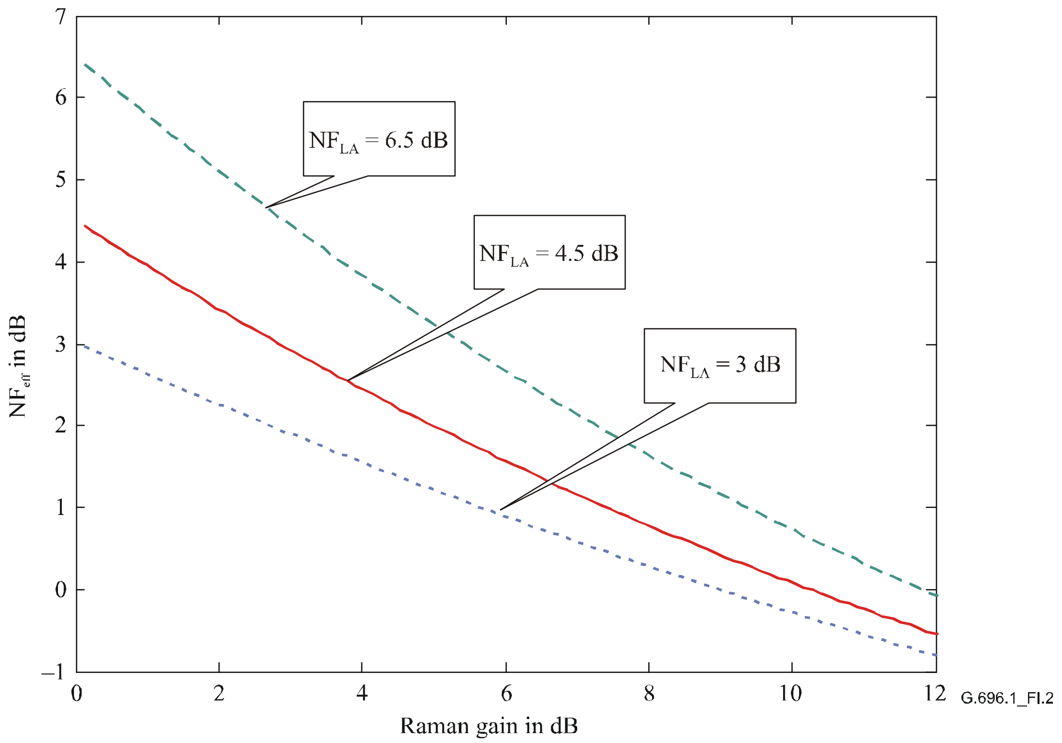

Figure I.2/G.696.1 – NF_{eff} as a function of Raman gain

NF_{eff} as a function of Raman gain G_{Raman} is shown in Figure I.2. Here, the following parameters are assumed: Fibre length 80 km, attenuation coefficient 0.275 dB/km and 0.3 dB/km for signal and pump wavelength, respectively, effective area of fibre 80 µm² and Raman gain coefficient 3.1E-14. The noise figures of the EDFA are 3 dB, 4.5 dB and 6.5 dB, respectively. The maximum transmission distance with Raman – EDFA combined amplifiers can be estimated by inserting NF_{eff} from Equation I-2 in the OSNR Equation I-1 and using $L = G_{Raman} + G_{LA}$ where again G_{LA} is the gain of the line amplifier in dB.

Assuming a Raman gain of approximately 9.3 dB and an EDFA noise figure of $NF_{LA} = 6.5$ dB, we get an effective noise figure of $NF_{eff} = 1$ dB which gives the dashed curve shown in Figure I.1.

Now the theoretical limiting distance without FEC becomes 19 spans and the addition of G.709/Y.1331 FEC would allow a system with more than 40 spans.

I.1.2 PMD

The total PMD of a fibre link, with total length L and a PMD coefficient for the individual cable sections PMD_Q, is given by $PMD = \sqrt{L} \cdot PMD_Q$. For a 10 Gbit/s NRZ interface, the total PMD should not exceed 10 ps (corresponding to an outage probability with "five nines" for a fibre induced maximum DGD = 30 ps). If the PMD coefficient PMD_Q value is not greater than 0.5 ps/km$^{1/2}$, this gives a total link length of 400 km; and with a maximum PMD coefficient $PMD_Q = 0.2$ ps/km$^{1/2}$, the total link length becomes 2500 km, see Figure I.3.

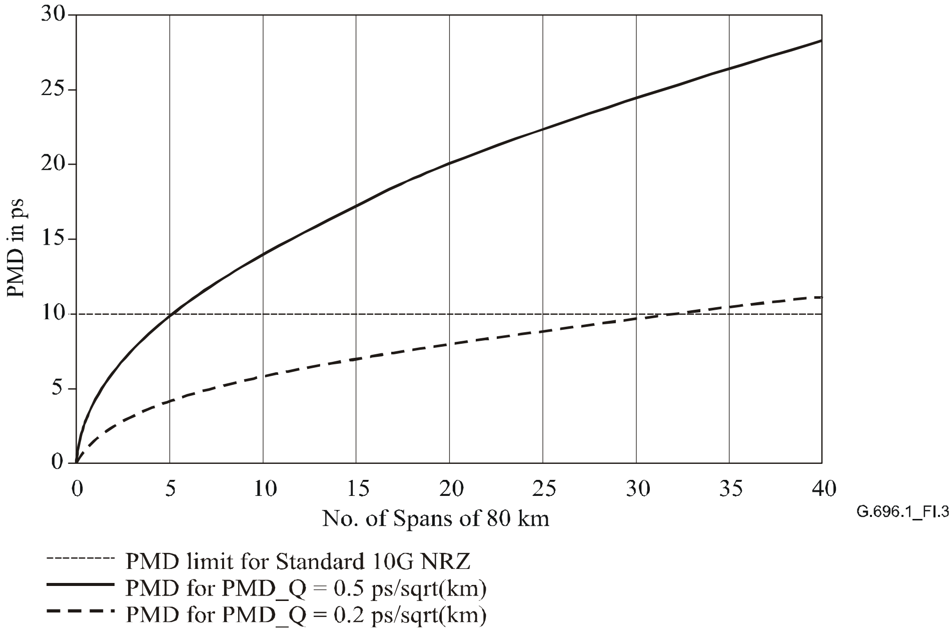

Figure I.3/G.696.1 – PMD vs distance for different PMD coefficients and PMD limit for 10 Gbit/s NRZ systems with 99.999% availability

Figure I.3 gives the guidance on maximum distance allowed according to fibre's maximum PMD_Q for NRZ line coding based on its 1st-order DGD tolerance. The figure has not accounted for the PMD contribution from equipment.

A real system on a real fibre link should consider the PMD limit from the combined contribution of both fibre link and equipment which comprises all the nodes in a link.

In some circumstances, higher-order PMD should also be considered.

I.2 Other effects which limit transmission distance

The limiting link distances calculated in the previous clauses are the distances that might be achieved in ideal circumstances. There are, however, several effects in practical systems that reduce the maximum link length.

I.2.1 Accumulated gain ripples from EDFA cascading and tilt due to stimulated Raman effects

A real system in a real link needs to consider power divergence among channels due to accumulated gain ripple and stimulated Raman effects.

Technologies like gain flattening filters and dynamical gain/power equalization can be used to reduce the impact of such effects, but there will still be some impact, which will reduce the achievable distances to less than those shown in Figure I.1.

I.2.2 Non-uniform span length

The application codes in this Recommendation consider equal span lengths. For the discussion in this appendix, a constant attenuation of 22 dB per span has been used. In real systems, the span lengths are usually not equal, actually depending on the real network topology and topographical constraints.

It is difficult to account for this "non-ideality" in a general manner, because, for the same system, longer spans mean an OSNR "debt" and shorter spans turn into an OSNR "credit".

The OSNR "debt" due to longer spans can be partially or completely compensated by increasing the output power of the amplifier preceding the span itself, provided that the increased power does not cause non-linear effects that cannot be tolerated without extra penalty.

Therefore, generally speaking, a link with longer spans may likely force the system to support a smaller number of spans, whereas a link with shorter spans may likely allow the system to support a larger number of spans. Given that this matter falls in the specific system design of the equipment vendor, it is simply mentioned here to give a more comprehensive view on these types of applications, without giving any details.

I.2.3 Optical non-linearity

Non-linear effects like Self-Phase Modulation (SPM) and/or Cross-Phase Modulation (XPM) accumulate over spans and become significant as the number of spans becomes large. Thus, non-linear penalty may not be ignored in a real link.

Higher channel power is good for OSNR, but is not necessarily good for BER. This is due to fibre non-linear effects.

Considering NRZ with average channel power of 3 dBm on G.652 fibre (the same power assumed in Figure I.1), accumulated non-linear (SPM) phase, $\Phi_{NL} = \gamma P_{ch} L_{eff} N_{span}$ after 10 spans is close to 1 radian and transmission is in a so-called "strong non-linear distortion" region where link distance may be non-linearity limited. Thus, the total link length could be much less than that predicted by Figure I.1 based on OSNR limits alone.

Further details of optical non-linearity are given in ITU-T Rec. G.663 and in ITU-T Supplement G.39 and some methods of mitigating these effects are discussed in clause I.3.

I.2.4 Residual dispersion and dispersion tolerance

The curves in Figure I.1 assume that each channel in the WDM system is perfectly dispersion compensated. While Dispersion Compensation Modules (DCMs) with an exactly inverse dispersion vs. wavelength slope to that of the fibre could be used, this is not usually the case and even then, higher order chromatic dispersion may need to be considered as the number of spans increases.

In addition to the mismatched slopes causing residual dispersion for some of the WDM channels, non-linear distortion can, if not mitigated, broaden the spectrum and thus reduce the dispersion tolerance after fibre transmission.

For example, for periodic dispersion compensated fibre link, non-linearity causes negative chirp which narrows dispersion compensation tolerance and moves the optimal dispersion compensation point to positive net dispersion. This effect is illustrated in Figure I.4.

This example is based on simulation of an eight-channel DWDM system with NRZ 10G signals over 10×80 km of G.652 fibre at an average output power of 3 dBm per channel. The simulation assumed that the chromatic dispersion of each 80 km section was exactly compensated at each line amplifier.

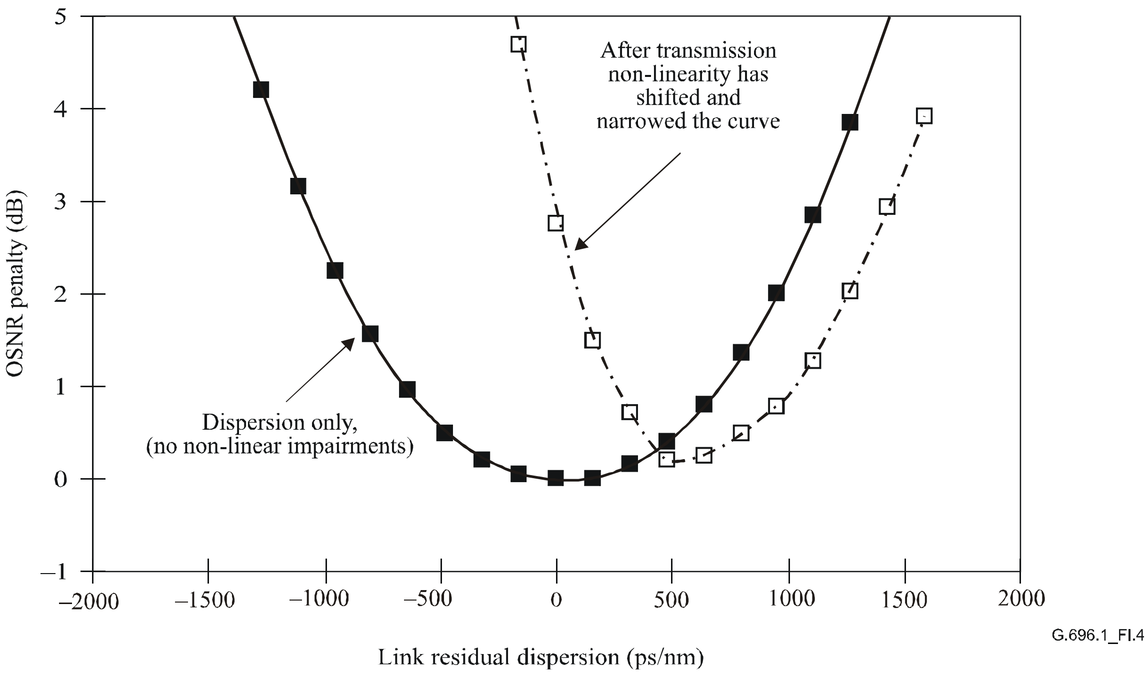

Figure I.4/G.696.1 – Example of the effect of non-linearity on dispersion tolerance after transmission

I.2.5 Accumulated PDL effects

Optical components such as WDM filters, VOAs or OAs exhibit finite Polarization Dependent Loss (PDL) that may range from 0.1 to 0.3 dB per device or even more. PDL exerts stochastic intensity modulation on optical signals due to variations in the signal polarization with time. The induced power fluctuations are transformed at OAs under the effects of Polarization Dependent Gain (PDG) into OSNR fluctuations.

In an extended 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. However, the correlation between power fluctuations and OSNR variations may not necessarily be one-to-one. The power fluctuations may be too fast to be fully compensated by means of dynamic gain equalization.

I.3 Techniques used to mitigate impairments

There are several practical techniques which may improve the performance of an IaDI link, such as by choosing:

i) dynamic gain equalization;

ii) line coding;

iii) number of optical channels and their spacing;

iv) fibre types;

v) mixing different types of fibre within one span.

I.3.1 Dynamic gain equalization

In order to compensate for the gain tilt introduced by a long chain of amplifiers, the use of an integrated optical spectrum analyzer (OSA) or optical power monitor (OPM) and adjustable gain flattening filters can be used to ensure good equalization across all the channels of the DWDM aggregate signal.

I.3.2 Modulation format

Modulation formats other than NRZ can provide some advantages under certain circumstances.

As described in ITU-T Supplement G.39, return to zero (RZ) line coded systems are significantly more tolerant to first-order PMD than NRZ systems. Also, modified RZ coding formats, such as phase-modulated RZ, can be additionally advantageous in terms of enhanced non-linear tolerance. These characteristics encourage the use of RZ line coding for very long link distances where PMD and non-linear effects are particularly significant.

On the other hand, RZ coding has (due to the broader bandwidth to be used) a potential drawback of being less spectrally efficient compared to NRZ (see ITU-T Supplement G.39) and is usually more sensitive to residual chromatic dispersion than NRZ. For this reason, systems that adopt RZ modulation format require a more precise characterization and compensation of the dispersion associated with the link.

Line codes other than NRZ and RZ can also be applied to DWDM systems, each of them having benefits and drawbacks. In particular, for very long link lengths and ultra-high capacity DWDM signals, the choice of a particular line code depends on the individual optimal system design.

I.3.3 Number of optical channels and their spacing

As a general trend, the maximum number of DWDM channels giving acceptable performance will tend to decrease with increasing link length and/or decreasing optical channel spacing, due to the increased impact of optical non-linearity.

I.3.4 Fibre types

One fibre type may have an advantage or disadvantage compared with another under certain conditions. In the C-band for example, G.652 has larger chromatic dispersion than G.655 or G.653 fibre and, therefore, it may introduce less non-linear effects. However, Raman gain strongly depends on fibre type and G.652 fibres, due to their large mode field diameters, show a smaller Raman gain for a given pump power than other fibres.

I.3.5 Mixing different types of fibre within one span

One technique that can be used to mitigate the effects of fibre non-linearity is to deliberately mix fibres with different characteristics within a single span. For example, a span containing alternating fibres with positive and negative dispersion results in a span with a high value of local dispersion (desirable to reduce the effects of XPM and four wave mixing (FWM)) but a low net dispersion (which reduces the dispersion compensation requirements).

In cases where a link has different fibre types in different spans, the launch power may have to be different in each span depending on the fibre types of the first 20 km of each span, in order to minimize the non-linear distortion.

I.4 Practical example

From the preceding discussion, it is clear that the number of spans that can be practically achieved for a given channel spacing, operating wavelength region, bit rate and span loss depends upon many system design choices such as which FEC scheme to employ, whether to use dynamic gain equalization or whether to use Raman amplification, etc.

However, as an example of available technology, a system with the following attributes:

- Minimum channel spacing: 100 GHz;
- Operating wavelength region: C band (1530 to 1565 nm);
- Client class: 10G;
- Span loss: 22 dB;

- G.652 fibre type;
- G.709/Y.1331 FEC,

can currently be cost effectively provided up to a maximum of about 15 spans.

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