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

Transmission media and optical systems characteristics – Characteristics of optical systems

# Longitudinally compatible intra-domain DWDM applications

Recommendation ITU-T G.696.1

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# Recommendation ITU-T G.696.1

## Longitudinally compatible intra-domain DWDM applications


### Summary

Recommendation ITU-T G.696.1 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.

In this version of this Recommendation, the following topics have been added with respect to the version from 07/2005:

- Client class 100G;
- Additional text for clause 8 "Optical safety considerations";
- Comprehensive revision of Appendix I including new clauses I.2.6, I.3.6, I.3.7, I.4, I.5 and additional text for some clauses.



### History

| Edition | Recommendation | Approval | Study Group |
|---|---|---|---|
| 1.0 | ITU-T G.696.1 | 2005-07-14 | 15 |
| 1.0 | ITU-T G.696.1 (2005) Erratum 1 | 2006-03-16 | 15 |
| 2.0 | ITU-T G.696.1 | 2010-07-29 | |

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## Recommendation ITU-T G.696.1

# 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

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.650.2] Recommendation ITU-T G.650.2 (2007), *Definitions and test methods for statistical and non-linear related attributes of single-mode fibre and cable*.

[ITU-T G.652] Recommendation ITU-T G.652 (2009), *Characteristics of a single-mode optical fibre and cable*.

[ITU-T G.653] Recommendation ITU-T G.653 (2006), *Characteristics of a dispersion-shifted single-mode optical fibre and cable*.

[ITU-T G.654] Recommendation ITU-T G.654 (2006), *Characteristics of a cut-off shifted single-mode optical fibre and cable*.

[ITU-T G.655] Recommendation ITU-T G.655 (2009), *Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable*.

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

[ITU-T G.664] Recommendation ITU-T G.664 (2006), *Optical safety procedures and requirements for optical transport systems*.

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

[ITU-T G.691] Recommendation ITU-T G.691 (2006), *Optical interfaces for single channel STM-64 and other SDH systems with optical amplifiers*.

[ITU-T G.707] Recommendation ITU-T G.707/Y.1322 (2007), *Network node interface for the synchronous digital hierarchy (SDH)*.

[ITU-T G.709] Recommendation ITU-T G.709/Y.1331 (2009), *Interfaces for the Optical Transport Network (OTN)*.

[ITU-T G.870] Recommendation ITU-T G.870/Y.1352 (2010), *Terms and definitions for optical transport networks (OTN)*.

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

[ITU-T G.957] Recommendation ITU-T G.957 (2006), *Optical interfaces for equipments and systems relating to the synchronous digital hierarchy*.

[ITU-T G.959.1] Recommendation ITU-T G.959.1 (2009), *Optical transport network physical layer interfaces*.

[IEC 60825-1] IEC 60825-1 (2007), *Safety of laser products – Part 1: Equipment classification and requirements*.

[IEC 60825-2] IEC 60825-2 (2007), *Safety of laser products – Part 2: Safety of optical fibre communication systems (OFCS)*.


# 3 Definitions

## 3.1 Terms defined elsewhere

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

**3.1.1** intra-domain interface (IaDI);

**3.1.2** 3R regeneration.

This Recommendation uses the following term defined in [ITU-T G.870]:

**3.1.3** optical channel data unit (ODUk).

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

**3.1.4** optical tributary signal.

## 3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

**3.2.1 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 G.707], this would be the rate of the ODUk.

**3.2.2 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 G.707].

**3.2.3 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 G.707] and ODU1 bit rate according to [ITU-T G.709].

**3.2.4 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 G.707] and ODU2 bit rate according to [ITU-T G.709].

**3.2.5 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 G.707] and ODU3 bit rate according to [ITU-T G.709].

**3.2.6 client class 100G**: Applies to a continuous digital signal with a client bit rate from nominally 39 Gbit/s to nominally 105 Gbit/s. The client class 100G includes a signal with ODU4 bit rate according to [ITU-T G.709].

## 4 Abbreviations and acronyms

This Recommendation uses the following abbreviations:

| | |
|---|---|
| 3R | (Regeneration) Re-amplification, Reshaping and Retiming |
| APR | Automatic Power Reduction |
| ASE | Amplified Spontaneous Emission |
| ASK | Amplitude Shift Keying |
| BER | Bit Error Ratio |
| DCM | Dispersion Compensation Module |
| DEMUX | Demultiplexer |
| DGD | Differential Group Delay |
| DP | Dual Polarization |
| DPSK | Differential Phase Shift Keying |
| DQPSK | Differential Quadrature Phase Shift Keying |
| 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 |
| ODB | Optical Duobinary |

| | |
|---|---|
| ODUk | Optical channel Data Unit k (k = 1, 2 or 3) |
| OPM | Optical Power Monitor |
| OSA | Optical Spectrum Analyser |
| OSNR | Optical Signal-to-Noise Ratio |
| PDG | Polarization-Dependent Gain |
| PDL | Polarization-Dependent Loss |
| PM | Polarization Multiplexing |
| PMD | Polarization Mode Dispersion |
| $PMD_Q$ | Statistical parameter for link PMD |
| PSK | Phase Shift Keying |
| QPSK | Quadrature Phase Shift Keying |
| RZ | Return to Zero |
| SOP | State of Polarization |
| 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 G.663], or Raman amplifiers according to [ITU-T 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.

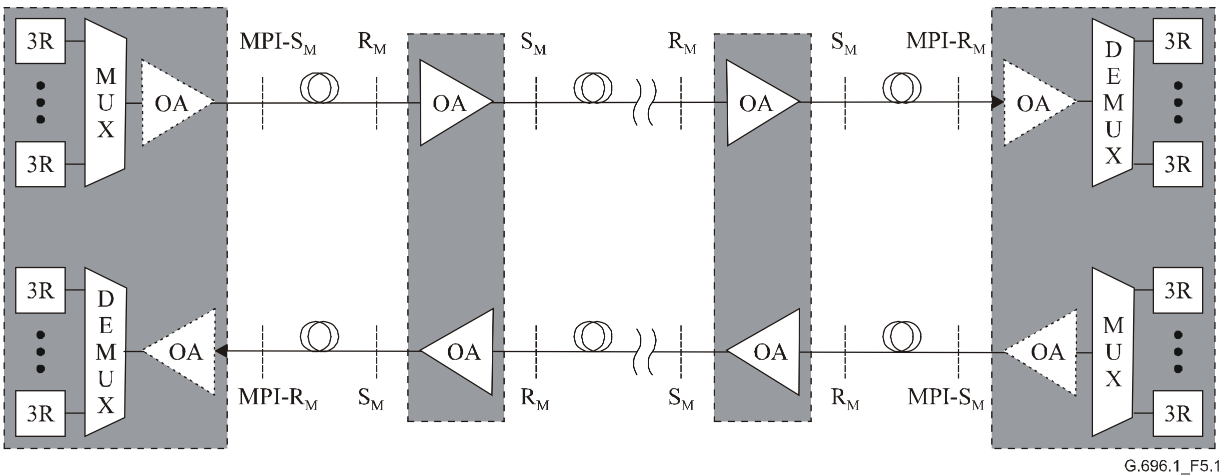


**Figure 5-1 – Reference configuration for a multi-span DWDM system**

The reference points in Figure 5-1 are defined as follows, using the same nomenclature as in [ITU-T 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;
- 100G indicating a client bit rate in the range from 39 Gbit/s to 105 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 [b-ITU-T G-Sup.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 [b-ITU-T G-Sup.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 – 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 – 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 – 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 [b-ITU-T G-Sup.39]. See Table 7-4.

**Table 7-4 – 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 ITU-T 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 ITU-T 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 clause 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 $A_{min}$ ($W$) defined by the letter "W" (see Table 7-2), and the attenuation coefficient $\alpha(s)$ in the operating wavelength range "s" (see clause 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 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 G.663] and in [b-ITU-T G-Sup.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:

$DGDmax_{link}$ is the maximum link DGD (ps)

$DGDmax_F$ 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 $DGDmax_{link}$ being controlled by the value of the Maxwell adjustment factor taken from Table 7-5.

**Table 7-5 – 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 | $4.2 \times 10^{-5}$ | 4 | $7.4 \times 10^{-9}$ |
| 3.2 | $9.2 \times 10^{-6}$ | 4.2 | $9.6 \times 10^{-10}$ |
| 3.4 | $1.8 \times 10^{-6}$ | 4.4 | $1.1 \times 10^{-10}$ |
| 3.6 | $3.2 \times 10^{-7}$ | 4.6 | $1.2 \times 10^{-11}$ |
| 3.8 | $5.1 \times 10^{-8}$ | | |

Further details can be found in [ITU-T G.650.2] and [ITU-T G.691]. The value of $DGDmax_F$ (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 – 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 – 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 of [ITU-T 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 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 G.664], [IEC 60825-1], [IEC 60825-2] and [b-IEC/TR 61292-4].

The hazard level, as defined in [IEC 60825-2], of transmission equipment according to this Recommendation should be limited to hazard level 1M (if necessary through the use of APR procedures) in order that it can be operated in restricted locations.

# Appendix I

## Theoretical limits and design considerations for DWDM systems

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

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. In clause I.4, mixed transmission of 10 Gbit/s, 40 Gbit/s and 100 Gbit/s transmission wavelengths is analysed, and in clause I.5, 100G applications are indicated.

### 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 [b-ITU-T G-Sup.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, $\nu_r$ 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 [ITU-T G.709] 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 of [b-ITU-T 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.

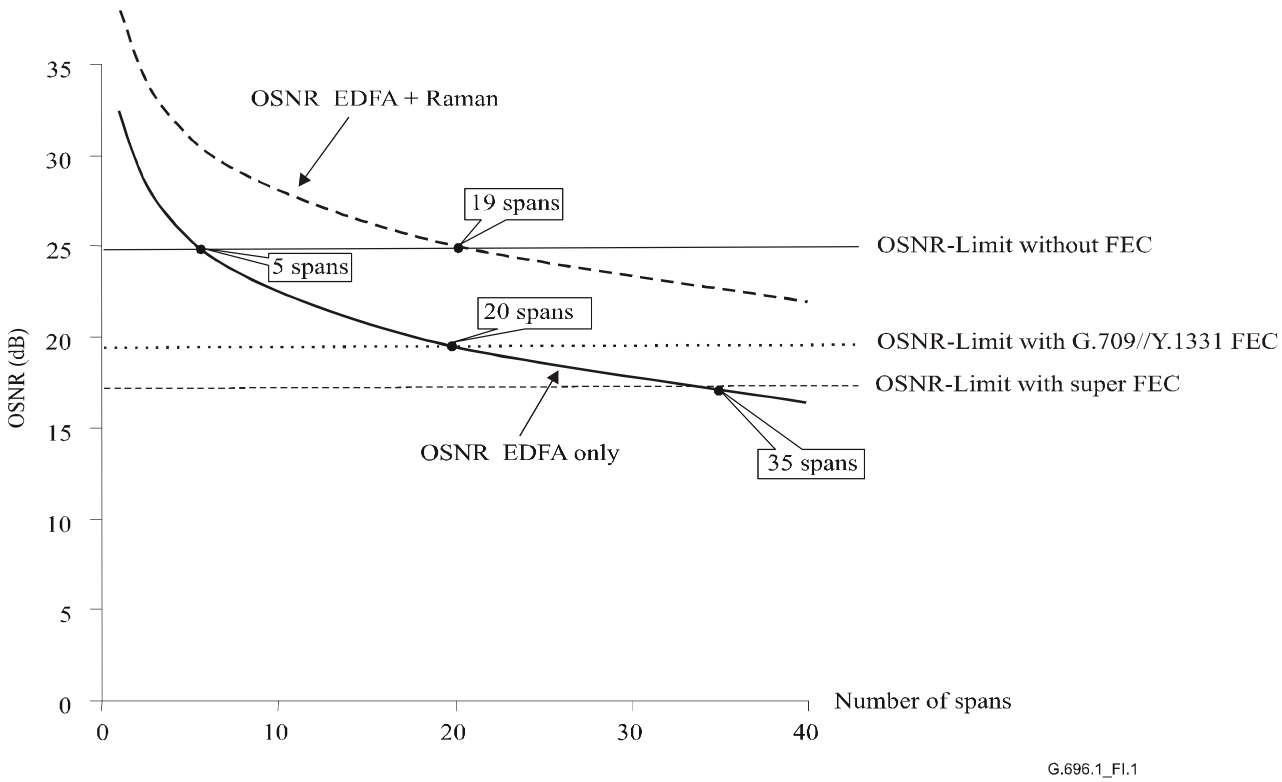


**Figure I.1 – OSNR limits for a reference system, OSNR as a function of span number with and without Raman amplification**

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 [b-Islam].

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

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, $\nu_r$ 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 [b-Aoki].

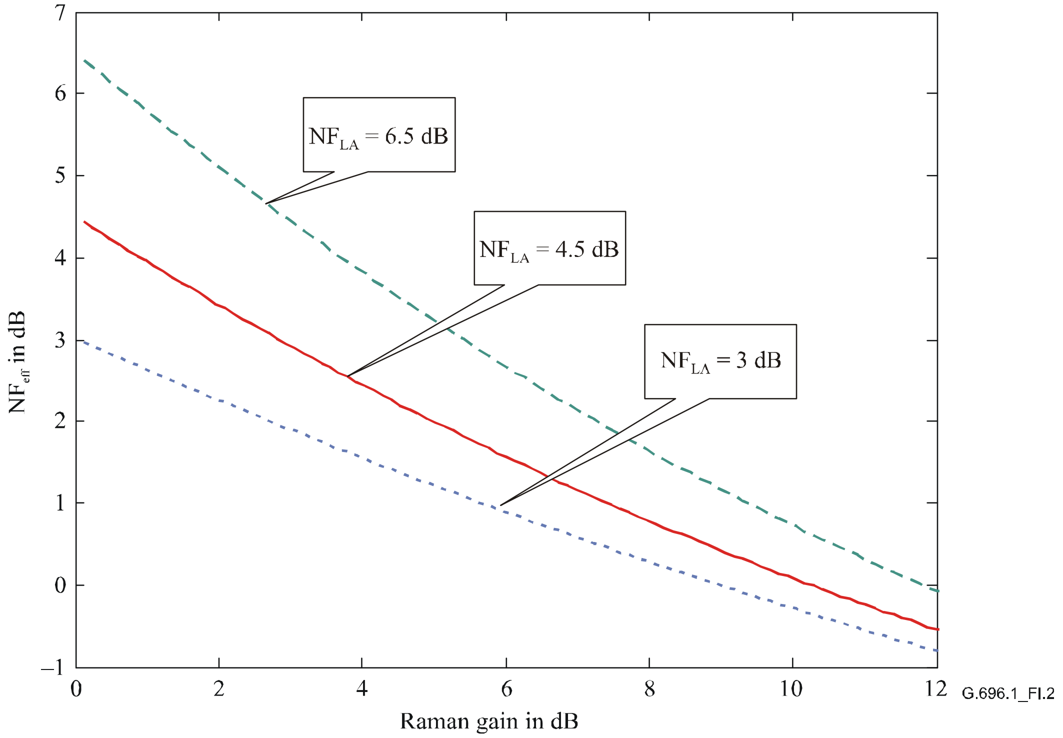


**Figure I.2 – $NF_{eff}$ as a function of Raman gain**

$NF_{eff}$ 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 [ITU-T G.709] 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.

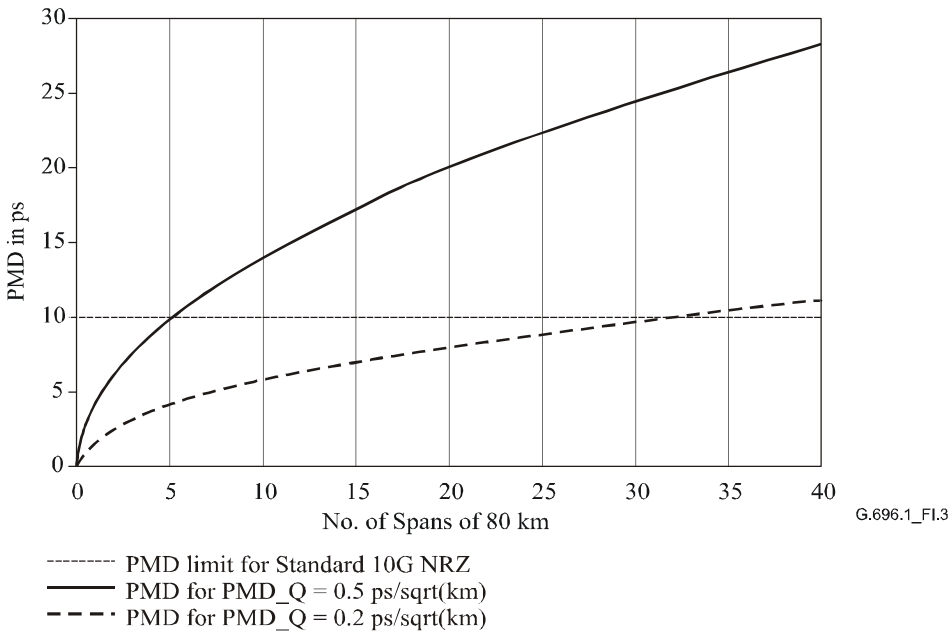


**Figure I.3 – PMD vs distance for different PMD coefficients and PMD limit for 10 Gbit/s NRZ systems with 99.999% availability**

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 ITU-T G.652 fibre (the same power assumed in Figure I.1), accumulated non-linear (SPM) phase shift, $\Phi_{NL} = \gamma P_{ch} L_{eff} N_{span}$ 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 and accurate dispersion management becomes mandatory. In the case of keeping the launched power at +3 dBm irrespective of the total number of spans, the non-linear SPM phase shift is increasing far beyond 1 radian. Aiming to achieve a constant 1 radian value for the whole transmission link, whatever the total number of spans is, results in an adaptation of the launched power versus number of spans.

Figure I.4 shows the comparison of the OSNR curve (EDFA only) from Figure I.1 (solid) applying constant fibre input power (P) value of 3 dBm together with the log(-N) adaptation (dotted) of fibre input power, where the non-linear SPM noise accumulation is a constant "integrated power product" (here 13 dBm) corresponding to a constant 1 radian of the non-linear phase shift. Thus, the two curves cross at 10 spans, showing a pessimistic and optimistic region of the solid curve compared to the dotted curve.

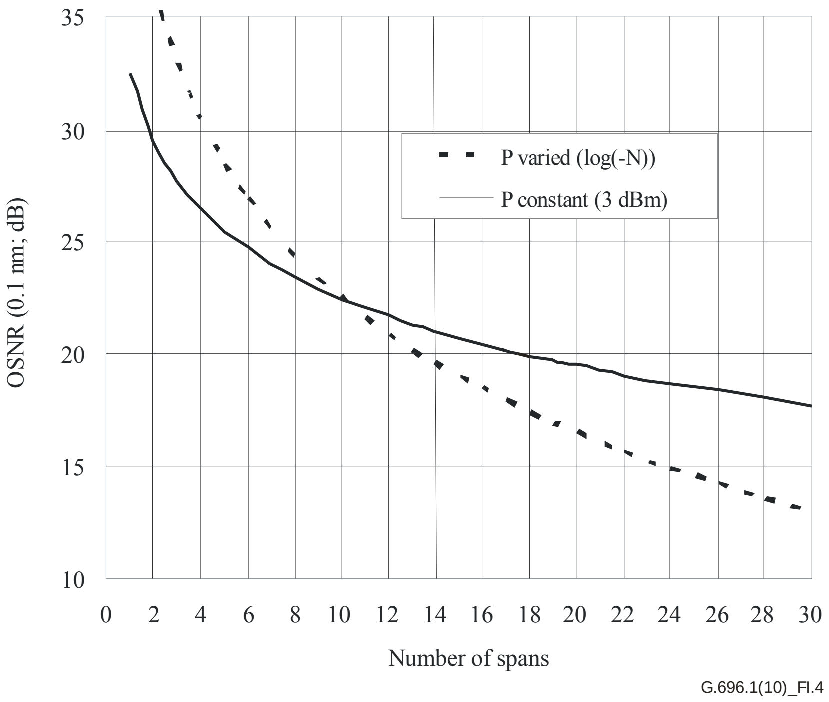


**Figure I.4 – OSNR versus No. of spans considering constant input power per span of 3 dBm and consideration of non-linear (SPM) phase accumulation according to variation of input power resulting in a reduction of input power per span according to log(-N)**

Further details of optical non-linearity are given in [ITU-T G.663] and in [b-ITUT G-Sup.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.5.

This example is based on simulation of an eight-channel DWDM system with NRZ 10G signals over 10 × 80 km of ITU-T 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.

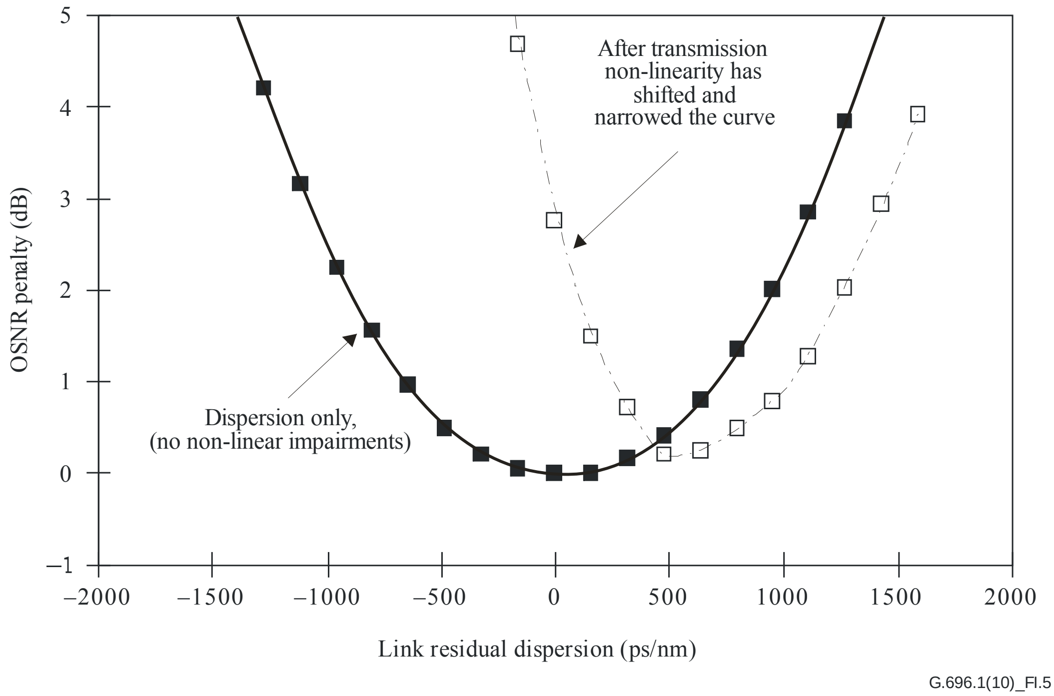


**Figure I.5 – Example of the effect of non-linearity on dispersion tolerance after transmission**

### 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.

In a WDM system utilizing polarization-multiplexed signals, PDL could change the state of polarization (SOP) and could degrade the degree of orthogonality in these signals, thereby degrading system performance.

### I.2.6 Filtering and crosstalk

As the symbol rate of the transmission system increases, the width of the spectrum becomes broader and can approach the width of the optical multiplexer and/or demultiplexer. Also the signal of phase shift keying (PSK) modulation formats is more sensitive to the phase response of the optical filter. Consequently, the signal may suffer from filtering of optical multiplexer and/or demultiplexer, resulting in the reduction of transmission distance.

Furthermore, the signal of broad spectrum bandwidth would also suffer from the finite isolation of optical multiplexer and/or demultiplexer, causing inter-channel crosstalk (refer to clause 9.6.2 in [b-ITU-T G-Sup.39]), which will consequently reduce the transmission distance.

### 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) modulation format;

iii) number of optical channels and their spacing;

iv) fibre types;

v) mixing different types of fibre within one span;

vi) receiver (detection scheme);

vii) digital equalization.

#### 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 analyser (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 [b-ITU-T G-Sup.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 [b-ITU-T G-Sup.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, ITU-T G.652 has larger chromatic dispersion than ITU-T G.655 or ITU-T G.653 fibre and, therefore, it may introduce less non-linear effects. However, Raman gain strongly depends on fibre type and ITU-T 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.3.6 Receiver (detection scheme)

In some higher speed transmission systems, other receivers can be used to enhance the performance of an IaDI link.

Differential detection and coherent detection receivers are useful in that they provide superior receiver sensitivity or OSNR tolerance to a conventional direct detection receiver (NRZ receiver) using a single photodiode, and this can lead to the achievement of long distance transmission.

In a differential detection receiver, the signal is mixed with a delayed signal (for example a 1-bit delayed signal) before the receiver. Differentially phase modulated optical signals are converted to amplitude modulated electrical signals using a delay optical interferometer and a balanced receiver. This differential detection provides approximately 3 dB higher sensitivity than direct detection because it can receive the signal with double the amplitude.

In a coherent detection receiver, the signal light is mixed with a reference light called a local oscillator, which has a frequency close to that of the signal. The output signal with a difference frequency contains the phase information of the original signal. The modulated optical signal is converted to an electrical signal, for example, through an optical hybrid and a balanced receiver. Digital coherent detection, where an analog to digital converter and a digital signal processor are used to estimate the carrier phase in the receiver, is useful for reducing phase noise. This process is linear and it can also compensate for impairments such as chromatic dispersion and PMD. It provides a sensitivity more than 3 dB higher than that provided by a direct detection receiver.

### I.3.7 Digital equalization

In some higher speed transmission systems, for the purpose of mitigating the effects of fibre non-linearity as much as possible, no inline chromatic dispersion compensation is adopted. Instead, the dispersion is compensated by digital equalization in conjunction with a coherent receiver, or alternatively, most compensation done by digital equalization in the receiver with a fraction of dispersion compensation done inline. Digital equalization is also able to compensate PMD.

## I.4 Mixed transmission of 10 Gbit/s, 40 Gbit/s and 100 Gbit/s transmission wavelengths

### I.4.1 Motivation for mixed 10G/40G/100G transmission

Transmission of 10G and 40G channels on the same fibre is of interest for operators for, at least, two reasons. Firstly, already installed networks designed for 10G transmission can be upgraded to 40G traffic. Secondly, networks designed for 40G traffic can be equipped with 10G wavelengths originating from low-traffic nodes.

Benefits of mixed transmission include the possibility to optimize the usage of fibre capacity by means of spectrally efficient modulation formats and, at the same time, to use lower-cost interfaces where 10G capacity is enough. When operating an optical transport network, several factors, including the cost of optical equipment, the fibre ownership, the power consumption and the physical space needed for the equipment must be taken into account. Hence, mixed 10G/40G transmission can be an attractive solution for minimizing the total cost of operations.

In current DWDM networks, most of the wavelengths are 10 Gbit/s and the modulation formats are purely amplitude shift keying (ASK) based on NRZ and RZ. However, in some applications including 40 Gbit/s, 100 Gbit/s and beyond, alternative modulation formats, including optical duobinary (ODB) or some form of phase shift keying (PSK) modulation format (see clause 7 of [b-ITU-T G-Sup.39]), can be used.

### I.4.2 Issues and challenges of mixed ASK/PSK signal transmission

In the mixed ASK/PSK system, the amplitude variation of the ASK channels can induce significant XPM to the co-propagating PSK channels. In such a system, the PSK signal may be influenced by the adjacent ASK signals and its performance may be degraded.

Interaction of ASK (NRZ and RZ) channels with PSK channels (such as DPSK, RZ-DQPSK, DP-QPSK and others) depends on several factors:

- modulation formats;
- channel plan (i.e., frequency spacing and location of channels in different formats);
- fibre type (i.e., ITU-T G.652, ITU-T G.653, ITU-T G.654 or ITU-T G.655), or mixed;
- the dispersion map;
- channel power levels;
- filter rejection;
- the polarization relation between the channels;
- symbol rates.

Regarding the symbol rate, higher symbol rate PSK signals often require more accurate dispersion management than 10 Gbit/s ASK signal alone in order to mitigate non-linearities and/or minimize dispersion penalty. An additional source of penalty from chromatic dispersion can be the coarse step of dispersion compensating modules used in the networks optimized for 10G ASK signals. Related issues are:

- optimal choice of pre-compensation for mixed ASK/PSK signal transmission;
- rearrangement (if required) of dispersion compensating modules to allow or improve PSK transmission in a network optimized for 10G ASK transmission;
- optimal post-compensation.

It is also known that the XPM impairment on PSK signals tends to be less when the symbol rate of the PSK channels is higher. References [b-Spinnler], [b-Griesser], [b-Vassilieva] contain further information.

In general, XPM is stronger the closer the spacing between the wanted channel and the disturbing channel, the higher the power of the disturbing signal and when there is polarization alignment between the two signals. These are factors that can be exploited in mitigation of non-linear penalty in a mixed system.

### I.4.3 Issues and challenges of mixed PSK/PSK signal transmission

If different channels employ phase shift keying (PSK), then additional challenges come into play. The large variety of possible modulation formats is indicated in clause 7 of [b-ITU-T G-Sup.39].

Although the modulation format is PSK, there may be some power fluctuation induced by filters, fibre dispersion, etc., during the transmission. These power fluctuations are similar to ASK signals, which can cause degradations on other PSK wavelengths via XPM.

## I.5 100G applications

There are certain points to be considered for 100 Gbit/s transmission. The OSNR limitation and the PMD limitation is crucial. In order to overcome the barriers, some advanced designs are necessary for 100 Gbit/s long distance (multi-span) transmission using amplifiers.

For instance, the combination of a dual polarization or polarization multiplexed (DP or PM) quadrature phase shift keying (QPSK) format with a digital coherent receiver can improve OSNR tolerance and compensate for impairments caused by PMD and chromatic dispersion.

An example of 112 Gbit/s DP-QPSK laboratory experimental result with a digital coherent receiver (with off-line processing) is shown in Figure I.6 which shows that the Q value vs OSNR and OSNR limitation (back-to-back) for BER = $10^{-4}$ (Q=11.4) is approximately 17 dB. The DGD tolerance for a 1 dB penalty is over 50 ps.

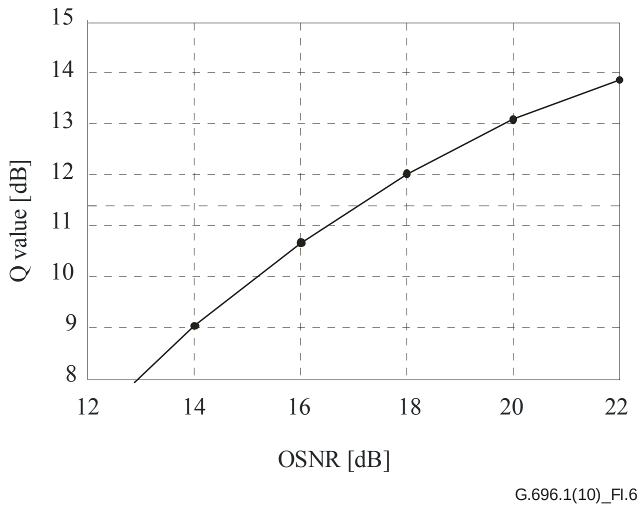


**Figure I.6 – Example of the Q value versus OSNR for 112 Gbit/s DP-QPSK signal**

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