CHAPTER 6

OPTICAL SYSTEMS: ITU-T CRITERIA FOR SPECIFICATIONS

Introduction

The real research phase of fibre-optic communication systems started around 1975. The enormous progress realized over the 30-year period extending from 1975 can be grouped into several distinct phases, which are described with some detail in the Introduction to this Handbook. During each phase, a "family" of optical systems had been developed, consistent with the corresponding ITU-T Recommendations. Some of these optical systems are still used, while others are obsolete.

The purpose of this Chapter is to outline the general specification criteria used in ITU-T for describing optical interfaces. The general objective of all ITU-T optical interface Recommendations is to achieve interworking among equipment from different manufacturers. In the cases where optical interworking is achieved, the relevant interfaces are called "transversely compatible interfaces". To this intent, an unambiguous and appropriate set of parameters and associated set of values is defined. In the cases where optical interworking is not achieved, the relevant interfaces are called "longitudinally compatible". This could be because optical technology isn't sufficiently mature or when design rules are significantly complex, whereby it was not possible to generate a specification of a transversely compatible interface with a reasonable amount of effort. Details on "transversely compatible interfaces" and "longitudinally compatible" interfaces are given in Clause 2.

This Chapter starts by giving the criteria used in ITU-T for the classification of the optical systems (Clause 1). A description of the ITU-T objectives for specifying each type of systems follows (Clause 2). Finally, the main parameters used for the specification are described (Clause 3).

1 Classification of the optical systems

Optical transmission systems can be classified by various criteria: operating wavelength range, single-channel and multichannel, type of WDM, bit rate and client classes, channel spacing and number of channels, characteristics of the interfaces, etc. These criteria are described in the following.

1.1 Operating wavelength range

(For further information see Recommendation ITU-T G.957 and Supplement 39 to the ITU-T G-series of Recommendations).

To provide a very high capacity for optical transmission systems, it is desirable to allow as wide a range as possible for the system operating wavelengths. The choice of operating wavelength range depends on several factors, including fibre type, source characteristics, system attenuation range, and dispersion of the optical path.

In ITU-T Recommendations, the following spectral bands are defined for single-mode fibre systems:

i) "Original" O-band, 1 260 nm to 1 360 nm.

The lower limit is determined by the cable cut-off wavelength, which is 1 260 nm. The upper limit 1 360 nm is determined by the rising edge of the "water" attenuation band peaked at 1 383 nm, so 1 360 nm was chosen as the upper limit;

ii) **"Extended" E-band, 1 360 nm to 1 460 nm.**

Recommendation ITU-T G.652 also includes fibres with a low water attenuation peak, which allows the utilization of the band above 1 360. The effects of a small water peak are negligible at wavelengths beyond about 1 460 nm;

iii) **"Conventional" C-band, 1 530 nm to 1 565 nm.**

Initially, erbium-doped fibre amplifiers (EDFAs) had useful gain bands beginning at about 1 530 nm and ending at about 1 565 nm. This gain band had become known as the "C-band";

iv) **"Short wavelength" S-band, 1 460 nm to 1 530 nm.**

The lower limit of this band is taken to be the upper limit of the E-band. The upper limit is taken to be the lower limit of the C-band. EDFAs have become available with relatively flatter and wider gains and application of EDFAs to this band is possible at least in a part of the band. Some wavelengths of this band may also be utilized for pumping of optical fibre amplifiers, both of the active-ion type and the Raman type;

i) **"Long wavelength" L-band, 1 565 nm to 1 625 nm.**

For the longest wavelengths above the C-band, fibre cable performance over a range of temperatures is adequate up to 1 625 nm for current fibre types;

vi) **"Ultra-long wavelength" U-band, 1 625 nm to 1 675 nm.**

In some cases it is desirable to perform a number of maintenance functions (preventive, after installation, before service and post-fault) on fibre cables in the outside plant. These involve surveillance, testing, and control activities utilizing optical time domain reflectometer (OTDR) testing, fibre identification, loss testing, and power monitoring. A wavelength region, that is intended to be never occupied by transmission channels, may be attractive for maintenance, even if enhanced loss occurs. The U-band has been defined exclusively for possible maintenance purposes. Transmission of traffic-bearing signals is not currently foreseen in this band. The use for non-transmission purposes must be done on a basis of causing negligible interference to transmission signals in other bands. Sufficiently low fibre loss is not ensured in this band.

Table 6-1 summarizes single-mode spectral bands:

Table 6-1 – Single-mode spectral bands

Band	Descriptor	Range [nm]
O-band	Original	1 260 to 1 360
E-band	Extended	1 360 to 1 460
S-band	Short wavelength	1 460 to 1 530
C-band	Conventional	1 530 to 1 565
L-band	Long wavelength	1 565 to 1 625
U-band	Ultra-long wavelength	1 625 to 1 675

The applicability of all of the wavelength bands, listed in Table 6-1, for system operation or maintenance purposes is not guaranteed by the ITU-T G.65x-series Recommendations, each of which in general cover a limited set of bands, depending on its application area.

1.2 Single-channel and multichannel system interfaces

Optical system interfaces can be divided in two broad categories: single-channel and multichannel interfaces.

On a_*single-channel interface* only one optical channel (one wavelength or frequency) is present on an optical fibre. One example is shown in Figure 6-1a), where an optical transmitter is connected to an optical receiver via an optical fibre.

On a *multichannel interface* several optical channels (several wavelengths or frequencies) are present on an optical fibre. One example is shown in Figure 6-1b). A multichannel system is generally described as a wavelength division multiplexing (WDM) system.

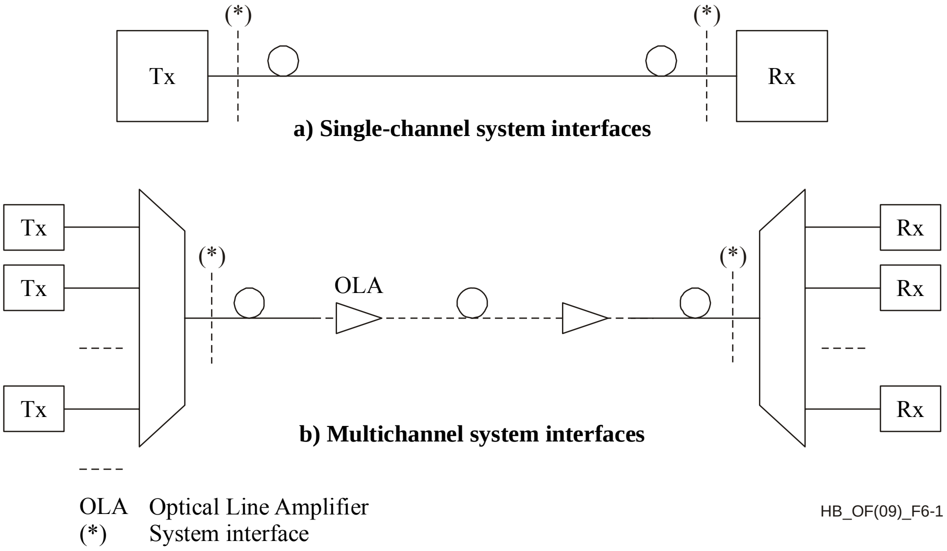

Figure 6-1 – Single-channel and multichannel systems

1.3 Channel spacing in WDM systems

The "Conventional" C-band defined above has a spectral range of 35 nm (1 530-1 565 nm, operating range of conventional optical fibre amplifiers), which exceeds 40 THz (0.8 nm = 100 GHz; 1 THz = 1 000 GHz).

Currently the maximum capacity of single-channel links is 40 Gbit/s.

A better utilization of the transmission capacity of an optical fibre can be obtained with the wavelength division multiplexing technique. With this technique multiple optical channels, each operating at a different wavelength, are combined on a single fibre by an optical multiplexer and then they are transmitted on the same fibre (Figure 6-1b). At the receive side the multiple signals are demultiplexed by an optical demultiplexer into separate optical channels. In this way, as an example, many 10 Gbit/s channels can be transmitted over the same fibre.

The ultimate capacity of a WDM fibre system depends on how closely optical channels can be packed in the wavelength domain. In the case of dense WDM (DWDM) applications optical channels are very densely spaced. For this case of DWDM applications the so-called "channel spacing" is expressed in the frequency domain. The maximum number of channels in a DWDM system operating in a given spectral band (e.g. 1 530-1 565 nm for the C-band) is determined by the channel spacing. For transversely compatible applications the channel spacing is fixed. Further details are provided in § 1.5.1. Current channel spacings specified in Recommendation ITU-T G.694.1 are multiples of 12.5 GHz up to a maximum of 100 GHz.

§ 1.5.1 also provides some further information for applications with channel spacing equal or larger than 200 GHz. Furthermore, there are some specific applications, e.g. operation on ITU-T G.653 fibres, where fixed channel spacing cannot be used because of the so-called four-wave-mixing (FWM) non-linear effect. Further details can be found in Chapter 7 of this Handbook.

The channel spacing is defined to be the nominal difference in frequency or wavelength between two adjacent optical channels. The minimum channel spacing is limited by interchannel crosstalk and it is related to many factors: the channel bit rate, the modulation format, the filter passband, and central wavelength variations (due to laser manufacturing and laser temperature variations).

1.4 Categories of WDM systems

Recommendation ITU-T G.671 defines three categories of WDM systems (Figure 6-2):

- i) *Coarse WDM* (CWDM), having a channel wavelength spacing less than 50 nm, but greater than 1 000 GHz (about 8 nm at 1 550 nm and 5.7 nm at 1 310 nm). The value of "c" (speed of light in vacuum) that should be used for converting between frequency and wavelength is 2.99792458×10^8 m/s;
- ii) *Dense WDM* (DWDM), having a channel spacing less than or equal to 1 000 GHz;
- iii) *Wide WDM* (WWDM), having a channel wavelength spacing greater than or equal to 50 nm.

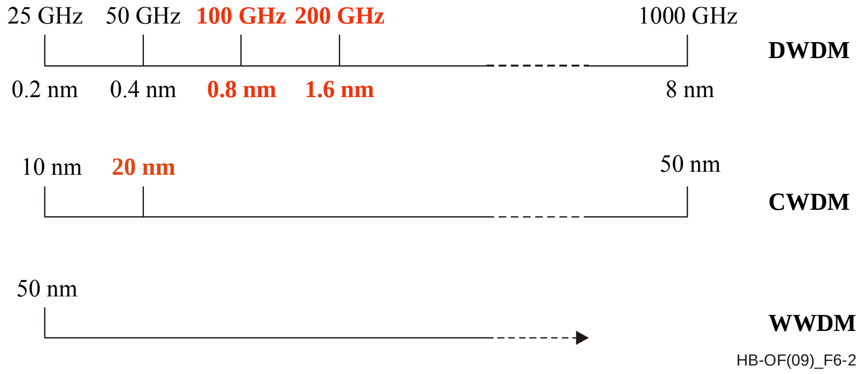

Figure 6-2 – Types of WDM systems

1.5 Number of channels in WDM systems

ITU-T uses "grids" for location of nominal central frequencies in WDM systems. Recommendation ITU-T G.694.1 defines a set of frequency grids for DWDM applications. Recommendation ITU-T G.694.2 defines a wavelength grid for CWDM applications. In a given spectral band (e.g. 1 530-1 565 nm for the C-band), the number of channels in a WDM system depends upon the particular channel spacing of the grid. At present a specification of a frequency grid for WWDM applications is not anticipated to be useful.

1.5.1 Number of channels in DWDM systems

In Recommendation ITU-T G.694.1, which provides the definition of frequency grids to support dense wavelength division multiplexing applications, currently four specific frequency grids are defined:

- i) 12.5 GHz spacing;
- ii) 25 GHz spacing;
- iii) 50 GHz spacing;
- iv) 100 GHz spacing.

All four frequency grids include 193.1 THz (1 552.52 nm) as one of their members, and there are no frequency limits beyond which the grid is not defined. This grid in fact is a "ruler" with no limits or end points.

Clause 6.2.2.1 of Supplement 39 to the ITU-T G-series Recommendations summarizes the above four frequency grids. In addition it shows that, using a specific formula, all the possible channel frequency grids can be derived.

Additional, wider spacing frequency grids can be used by taking integer multiples of 100 GHz spacing, i.e. 200 GHz, 300 GHz, 400 GHz, etc. The grids for these wider spacings are intentionally not specified to provide the user with complete freedom for choosing central frequencies.

ITU-T Recommendations defining applications that utilise these DWDM frequency grids include Recommendations ITU-T G.692, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1. The number of channels is not specified, but, as an indication, about 40 channels with 100 GHz spacing (100 GHz × 40 ch. = 4,000 GHz = 4 THz) can occupy the complete C-band of 1 530-1 565 nm. Of course, the number of channels can double when using a channel spacing of 50 GHz.

1.5.2 Number of channels in CWDM systems

Recommendation ITU-T G.694.2 provides the definition of a wavelength grid with channels spaced at 20 nm to support coarse wavelength division multiplexing applications. This CWDM grid has been initially defined to allow simultaneous transmission of several optical 2.5 Gbit/s signals with sufficient separation to permit the use of uncooled sources.

The channel spacing of 20 nm was determined mainly by three factors (Figure 6-3):

i) the laser manufacturer is allowed a wavelength variation around the nominal wavelength in order to achieve a higher yield and/or relax manufacturing tolerances;

ii) the laser wavelengths are allowed to change over a sufficiently wide temperature range to permit usage of uncooled lasers;

iii) a sufficiently wide guardband is left between the channels to allow the use of low cost filter technologies.

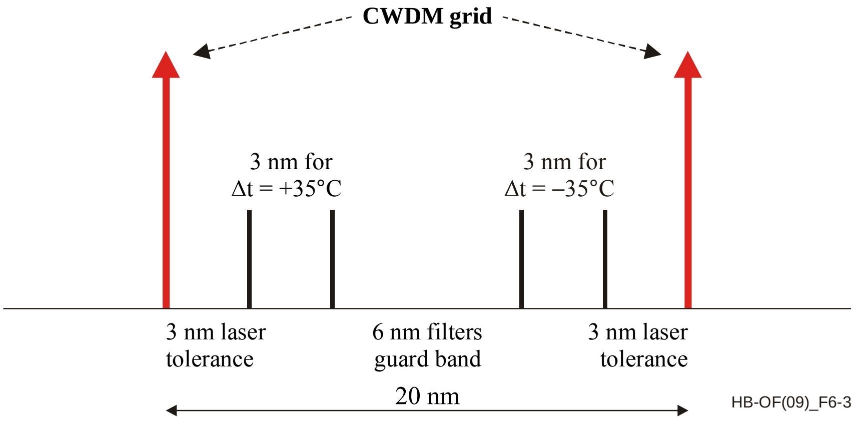

Figure 6-3 – Channel spacing for CWDM systems

The channel spacing of 20 nm allows the allocation of 18 wavelengths in the frequency range 1 271-1 611 nm. However, applications using this CWDM grid, specified in Recommendation ITU-T G.695, have a maximum of 16 optical channels (Figure 6-4).

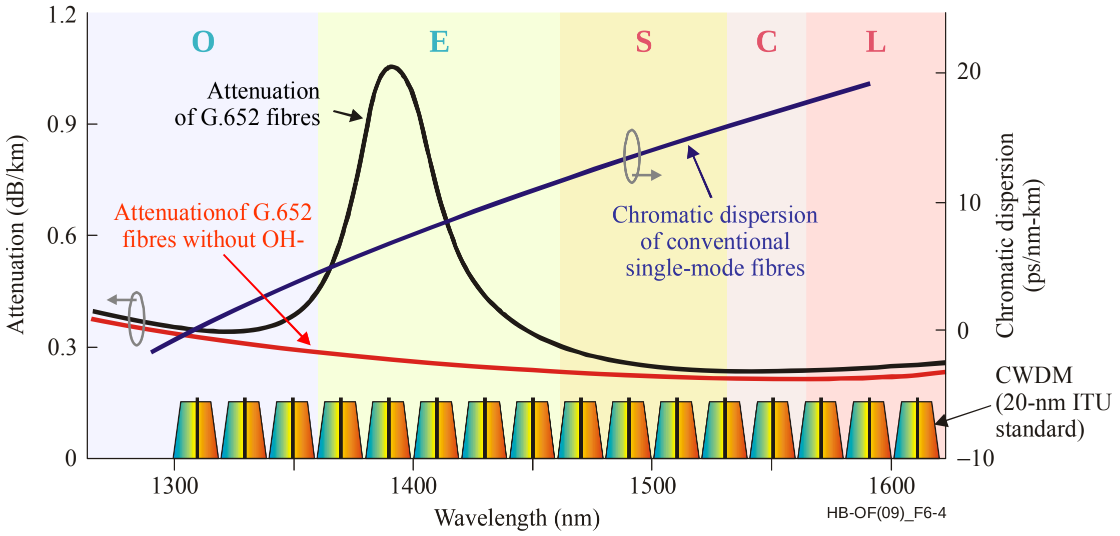

Figure 6-4 – Allocation of the CWDM channels

1.6 Bit rates and client classes

(For further information see Recommendation ITU-T G.959.1).

A single channel signal that is placed within (or converted to) an optical channel for transport across the optical network is called "optical tributary signal".

In ITU-T optical interface Recommendations, the digital optical signals are defined in the following different optical tributary classes:

i) optical tributary signal class NRZ 1.25G (non-return to zero), which applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 1.25 Gbit/s. Optical tributary signal class NRZ 1.25G includes a signal with STM-4 (synchronous transport module) bit rate according to Recommendation ITU-T G.707;

ii) optical tributary signal class NRZ 2.5G which applies to continuous digital signals with non-return to zero line coding, from nominally 622 Mbit/s to nominally 2.67 Gbit/s. Optical tributary signal class NRZ 2.5G includes a signal with STM-16 bit rate according to Recommendation ITU-T G.707 and OTU1 bit rate according to Recommendation ITU-T G.709;

iii) optical tributary signal class NRZ 10G which applies to continuous digital signals with non-return to zero line coding, from nominally 2.4 Gbit/s to nominally 10.76 Gbit/s. Optical tributary signal class NRZ 10G includes a signal with STM-64 bit rate according to Recommendation ITU-T G.707, OTU2 bit rate according to Recommendation ITU-T G.709 and OTL3.4 bit rate (OTU3 striped across four physical lanes) according to Recommendation ITU-T G.709;

iv) optical tributary signal class NRZ 25G which applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 28 Gbit/s. Optical tributary signal class NRZ 25G includes a signal with OTL4.4 bit rate (OTU4 striped across four physical lanes) according to Recommendation ITU-T G.709;

v) optical tributary signal class NRZ 40G which applies to continuous digital signals with non-return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class NRZ 40G includes a signal with STM-256 bit rate according to Recommendation ITU-T G.707 and OTU3 bit rate according to Recommendation ITU-T G.709;

vi) optical tributary signal class RZ 40G which applies to continuous digital signals with return to zero line coding, from nominally 9.9 Gbit/s to nominally 43.02 Gbit/s. Optical tributary signal class RZ 40G includes a signal with STM-256 bit rate according to Recommendation ITU-T G.707 and OTU3 bit rate according to Recommendation ITU-T G.709.

As a consequence, the bit rates of the optical signals foreseen in ITU-T Recommendations are the following: 1.25 Gbit/s, 2.5 Gbit/s, 10 Gbit/s, 25 Gbit/s and 40 Gbit/s.

1.7 Unidirectional and bidirectional systems

(For further information see Recommendation ITU-T G.692).

Unidirectional WDM is the transmission of all optical channels on a fibre propagating simultaneously in the same direction (Figure 6-5).

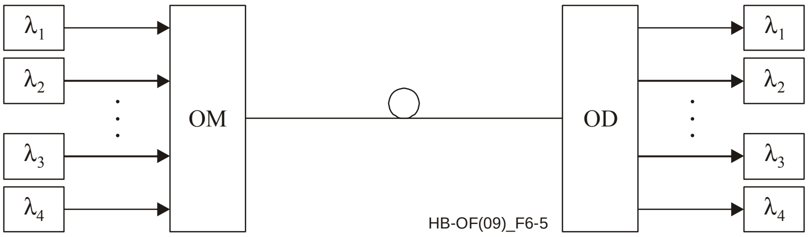

Figure 6-5 – Unidirectional WDM

Bidirectional WDM is the transmission of optical channels on a fibre propagating simultaneously in both directions (Figure 6-6).

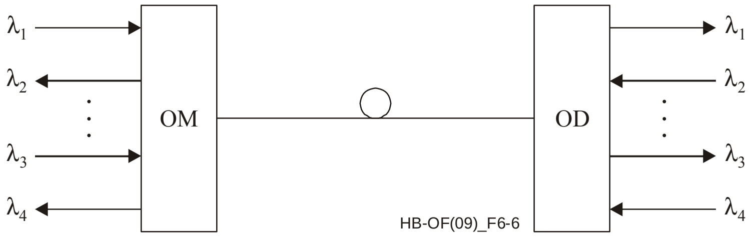

Figure 6-6 – Bidirectional WDM

Bidirectional WDM can lead (when a high number of channels is not required) to a reduction in the number of fibres and line amplifiers required, as compared to systems using unidirectional WDM. A further benefit of bidirectional WDM may be performance improvement with respect to four-wave mixing (FWM), particularly when being deployed with ITU-T G.653 fibres (See Chapter 7).

In bidirectional WDM designs, several key systems issues should be taken into account. Care must be taken to avoid optical reflections in order to prevent multi-path interference. Some additional considerations are types and values of crosstalk, values and interdependence of power levels for both directions of transmission, OSC (Optical Supervisory Channel) transmission (if present), and automatic power shutdown or reduction.

Optical interfaces with bidirectional transmission are currently only specified in ITU-T for CWDM systems (see Recommendation ITU-T G.695).

1.8 Linear and ring configurations

(For further information see Recommendation ITU-T G.698.2 and Supplement 39 to the ITU-T G-series Recommendations).

The generic representation of a linear configuration is shown in Figure 6-7 where the DWDM network elements include an optical multiplexer (OM) and an optical demultiplexer (OD), which are used as a pair with the opposing element, one or more optical amplifiers and may also include one or more OADMs. *n* WDM optical channels are carried on one output fibre of a multichannel transmitter equipment.

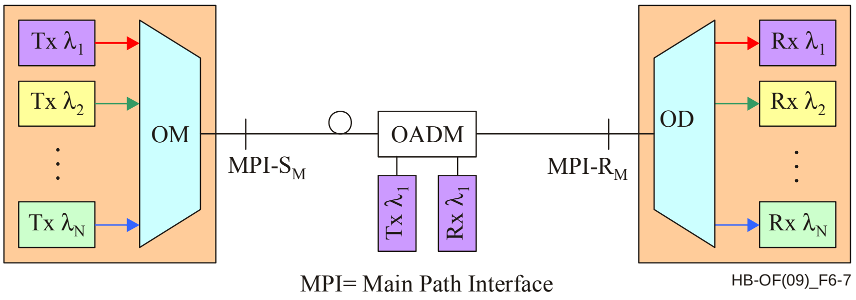

Figure 6-7 – Linear configuration

In Figure 6-8 an example is shown of a ring configuration where the DWDM network elements include one or more amplifiers and two or more OADMs connected in a ring.

1.9 Fibre type

Single mode optical fibre types are chosen for the optical systems from those defined in the ITU-T G.65x-series Recommendations.

1.10 Line coding

(For further information see ITU-T Supplement 39 to the ITU-T G-series Recommendations).

Optical interfaces defined, for example, in Recommendations ITU-T G.957, ITU-T G.691, ITU-T G.692 and ITU-T G.959.1, are currently based on non-return to zero (NRZ) transmission. The related parameters (as well as the definition of the logical "0" and logical "1") are defined in those Recommendations. For more demanding applications or transmission at rates of 40 Gbit/s or above, other line codes could be of advantage.

Return-to-zero (RZ) line-coded systems, for example, are significantly more tolerant to first-order PMD-induced DGD and could, therefore, be better suited for ultra-long-haul transmission of high rate signals. However, RZ coding has (due to the broader signal bandwidth) a potential drawback of being less spectrally efficient compared to NRZ (see Chapter 7).

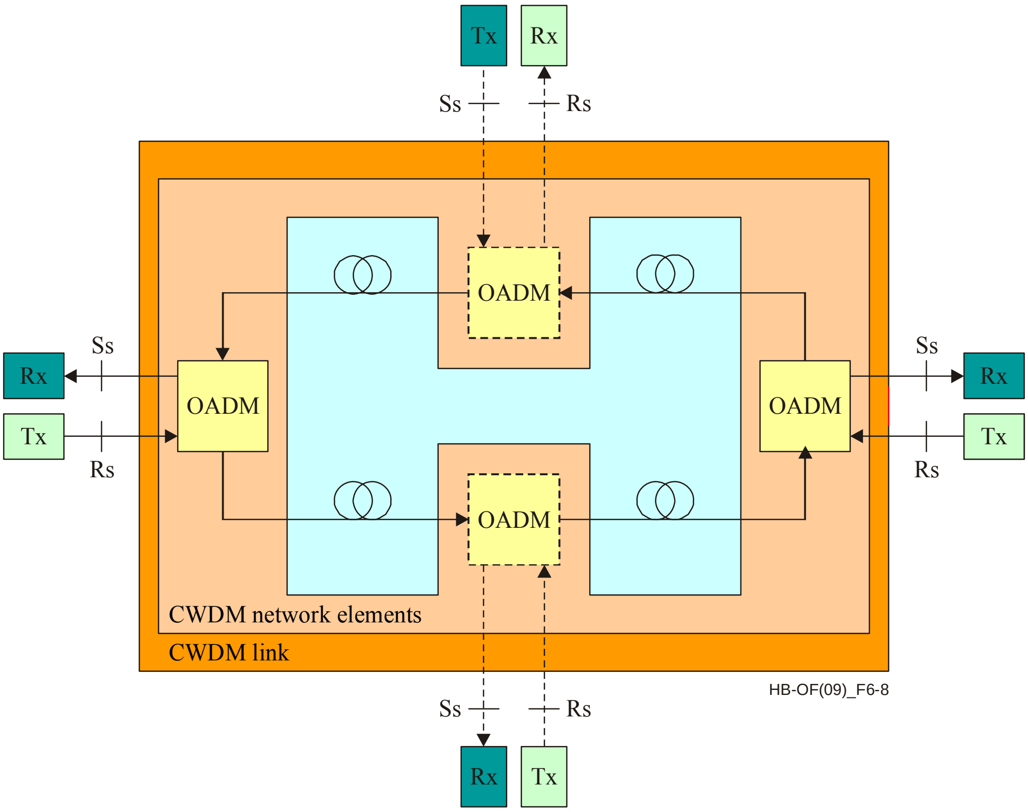

Figure 6-8 – Ring configuration

1.11 Bit Error Ratio

Because of noise inherent in any receiver, there is always a finite probability that a bit could be identified incorrectly by the decision circuit. Optical systems are generally designed to operate in such a way that the error probability in the digital receivers is smaller than a specified value (see Chapter 7).

Figure 6-9a) shows schematically the fluctuating signal received by the decision circuit, which is sampling the received signal at the decision instant (which is determined by clock recovery). The sampled value fluctuates from bit to bit around an average value I_1 or I_0 depending on whether the bit corresponds to 1 or 0 in the bit stream. The decision circuit compares the sampled value with a threshold value I_D (normally in the middle between the logical 1 and 0 levels if the same error probability is associated to these) and calls it bit 1 if $I > I_D$, or bit 0 if $I < I_D$. An error occurs if $I < I_D$ for bit 1 because of the receiver noise. An error also occurs if $I > I_D$ for bit 0. Both sources of errors are included in the error probability.

Figure 6-9b) shows that both the probability of an error on 1 and on 0 depends on the probability density of the sampled value I. The probability density depends on the statistics of noise sources responsible for current fluctuations.

All the system's parameters are specified in relation to an optical section design objective of a bit error ratio (BER) not worse than the value specified by the application code. In each application, this value applies to each optical channel under the extreme case of optical path attenuation and dispersion conditions.

For all applications in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2 and ITU-T G.959.1, an optical section design objective of an end-of-life BER not worse than 10^{-12} has been specified. The requirement for SDH applications is derived from Recommendation ITU-T G.826 and, more recently, from Recommendation ITU-T G.828, while corresponding requirements for OTN applications are given in Recommendation ITU-T G.8201.

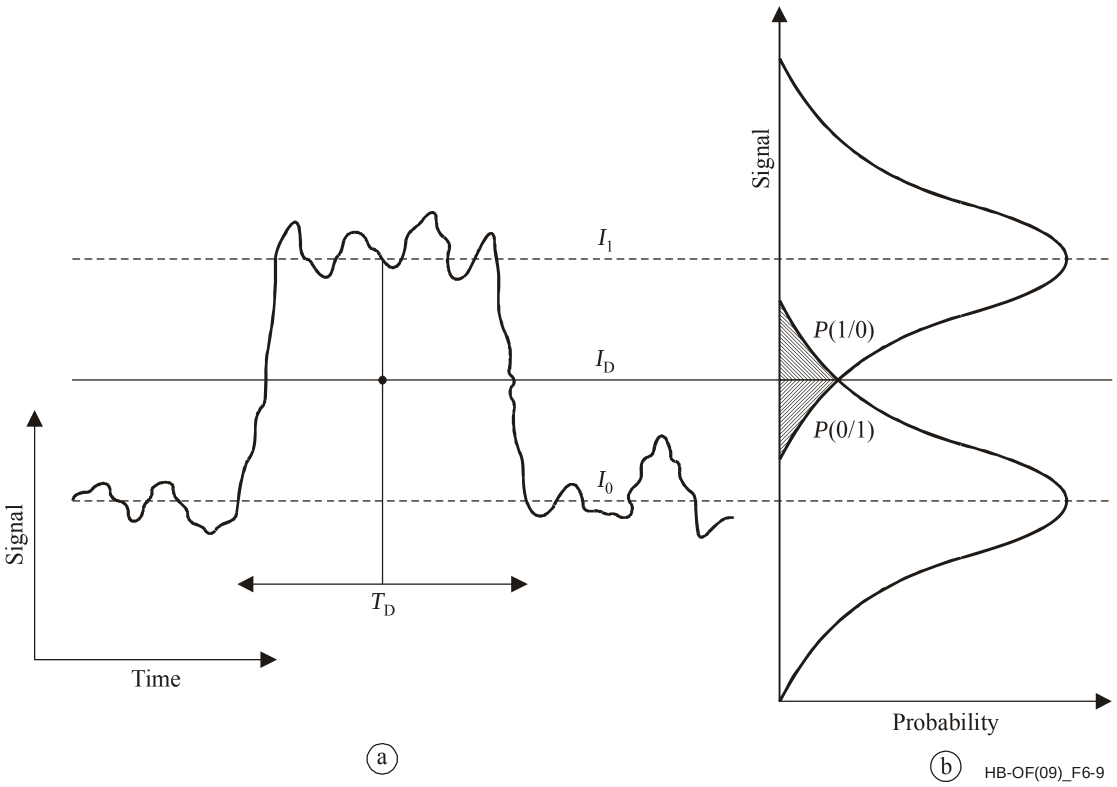

Figure 6-9 – Errors on bits

Applications in Recommendation ITU-T G.957, however, have an end-of-life BER requirement of 10^{-10} due to less stringent requirements being in place at the time of their development.

In order to "migrate" applications from a BER of 10^{-10} to 10^{-12}, a convention has been adopted where application codes with a maximum attenuation range of 12 dB at a BER of 10^{-10} were reduced to 11 dB at a BER of 10^{-12}, and application codes with a maximum attenuation range of 24 dB at a BER of 10^{-10} were reduced to 22 dB at a BER of 10^{-12}.

1.12 The Q-factor

(For further information see Supplement 39 to the ITU-T G-series Recommendations).

Often the Q-factor is used instead of the BER. As a matter of fact, the lower the value of the reference BER, the more difficult it is to actually verify the receiver performance, due to the extended measurement time required. Two approaches have been proposed to address this problem. The first is to use a particular length of error-free operation to establish a certain probability of the error rate being below the required level. The required number of error free bits (n) can be found as:

$$n = \frac{\log(1-C)}{\log(1-P_E)}$$

where:

C: required confidence level (e.g. 0.95 for 95% confidence), and

P_E: BER requirement (e.g. 10^{-12}).

Therefore, if a confidence level of 95% for the BER to be less than 10^{-12} is required, 3×10^{12} error free bits are needed (20 minutes at 2.5 Gbit/s).

Since this still requires long measurement times at lower rates, an alternative method is to measure the Q factor. The Q factor is the signal-to-noise ratio at the decision circuit in voltage or current units, and is typically expressed by:

$$Q = \frac{(\mu_1 - \mu_0)}{(\sigma_1 + \sigma_0)}$$

where $\mu_{1/0}$ is the mean value of the marks/spaces voltages or currents, and $\sigma_{1/0}$ is the standard deviation. A BER of 10^{-12} corresponds to $Q \approx 7.03$.

Since practical Q measurement techniques make measurements in the upper and lower regions of the received "eye" in order to infer the quality of the signal at the optimum decision level, Q can be considered as only a qualitative indicator of the actual BER.

The mathematical relations to BER (in case of non-FEC operation) when the threshold is set to the optimum value are:

$$BER = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

where:

$$\mathrm{erfc}(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-\frac{\beta^2}{2}}\, d\beta$$

A commonly used approximation for this function is: $BER \approx \frac{1}{Q\sqrt{2\pi}} e^{-\frac{Q^2}{2}}$

for $Q > 3$.

A graph comparing these mathematical relationships and the approximations for Q-values less than 5 is given in Figure 6-10.

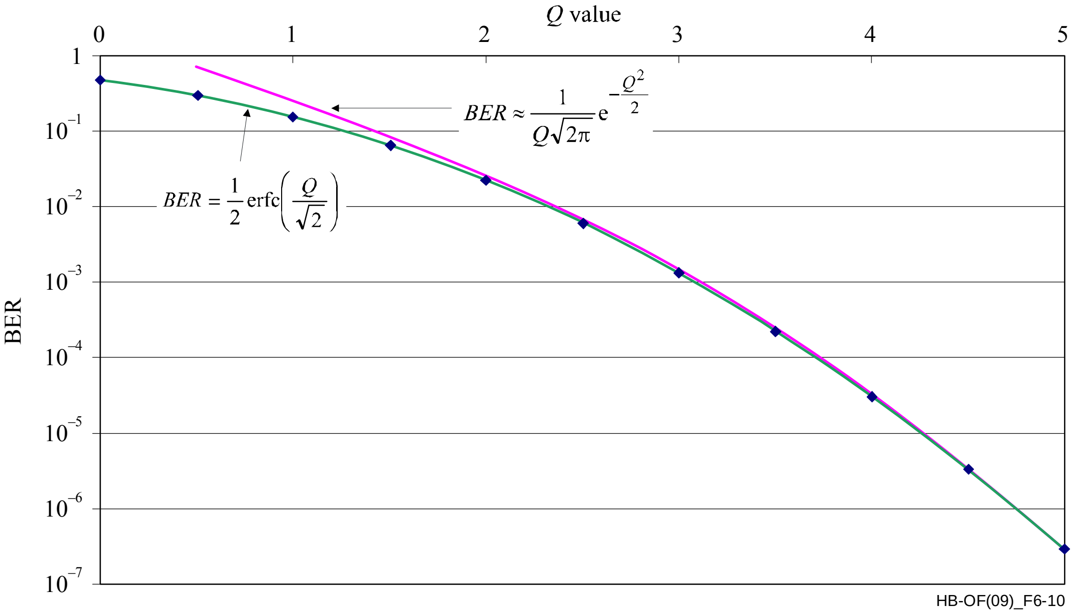

Figure 6-10 – Approximations relating BER and Q

1.13 Forward Error Correction

(For further information see Supplement 39 to the ITU-T G-series Recommendations).

Forward error correction (FEC) is rapidly becoming an important way of improving the performance of large-capacity long-haul optical transmission systems and is already well established in wireless communication systems. Employing FEC in optical transmission systems yields system designs that can accept relatively large BER before decoding (around 10^{-5} to 10^{-6}) in the optical transmission line. FEC application may allow the optical parameters to be significantly relaxed and encourages the construction of large capacity, long-haul optical transmission systems in a cost-effective manner.

Definitions of FEC terminology are provided in Table 6-2:

Table 6-2 – FEC terminology

Information bit (byte)	Original digital signal to be FEC encoded before transmission
FEC parity bit (byte)	Redundant bit (byte) generated by FEC encoding
Code word	Information bit (byte) plus FEC parity bit (byte)
Code rate R	Ratio of bit rate without FEC to bit rate with FEC ($R = 1$ for in-band FEC)
Coding gain	Reduction of Q values at specified BER (e.g. 10^{-12}) assuming white Gaussian noise and a theoretical reference receiver
Net coding gain (NCG)	Coding gain corrected by the increased noise due to bandwidth expansion needed for FEC bits assuming white Gaussian noise (out-of-band FEC)
Q b factor	Q factor corrected by the bandwidth expansion factor $1/\sqrt{R}$
BER_{in}	BER of the encoded line signal (= BER of the input signal of the FEC decoder)
BER_{out}	BER of the decoded client signal (= BER of the output signal of the FEC decoder)
BCH codes	Bose – Chaudhuri – Hocquenghem codes: the most commonly used BCH codes are binary codes
RS codes	Reed-Solomon codes: the most commonly used non-binary subclass of BCH codes
xxx (n, k) code	xxx = code class (BCH or RS) n = number of code word bits (bytes) k = number of information bits (bytes)

For the relevant optical interface Recommendations where application codes are specified with the mandatory use of FEC, it is indicated that the system BER is required to be met only "after the error correction has been applied". In these specific cases, the optical parameters are specified at a BER not worse than 10^{-12} at the FEC decoder output.

This is illustrated in Figure 6-11 which shows the theoretical BER at the receiver output (point A) is 1.8×10^{-4} for 10^{-12} BER at the FEC decoder output (point B).

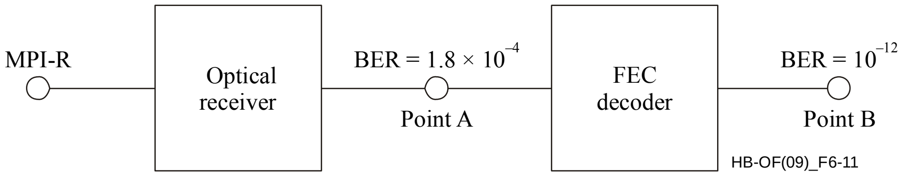

Figure 6-11 – Effect of usage of FEC on receiver performance in relation to BER

At present, two FEC schemes are recommended in ITU-T for optical transmission systems. They are *"in-band FEC"* for SDH systems, and *"out-of-band FEC"* for optical transport networks (OTNs). The terminology "in" or "out" refers to the client bandwidth. In-band FEC parity bits are embedded in a previously unused part of the section overhead of SDH signals, so the bit rate is not increased. In contrast to SDH, OTN signals including space for FEC bits (OTUk) have a higher bit rate than the equivalent signal before the FEC is added (ODUk). Therefore, OTN signals are encoded using out-of-band FEC, resulting in a slightly increased line-rate.

1.13.1 In-band FEC in SDH systems

The in-band FEC specified for SDH systems is described in Recommendation ITU-T G.707. The code is triple-error correcting binary BCH code, more exactly a shortened BCH (4359,4320) code. Up to three bit errors can be corrected in a 4359-bit code word. The code word is an 8-bit interleaved signal stream of 270 × 16 bytes from 1 row of the STM-N frame. Therefore, up to 24-bit continuous errors in each row of an STM-16, -64 or -256 frame can be corrected. Currently optical interface specifications for applications with in-band FEC are not provided by the ITU-T Recommendations concerned with optical interfaces.

1.13.2 Out-of-band FEC in optical transport networks (OTNs)

The out-of-band FEC specified for OTN (optical transport network) is described in Recommendation ITU-T G.709. This code is a symbol error correcting RS code. Up to eight bytes in the code word can be corrected. The frame employs 16-byte interleaving, so 1 024 bits continuous errors can be corrected. Currently optical interface specifications for applications with out-of-band FEC are provided in several ITU-T Recommendations (e.g. in Recommendations ITU-T G.698.2 and ITU-T G.959.1).

1.13.3 Coding gain and net coding gain

In the case of randomly distributed errors within the encoded line signal, a FEC decoder reduces the line or raw BER to a required reference BER value within the payload signal. Coding gain could therefore be regarded as the relation of these bit error ratios. In order to define a coding gain parameter as a more system-related parameter, the BER reduction by the FEC is usually transformed into a dB value based on a theoretical reference system. It is common practice to define the coding gain as the reduction of signal-to-noise ratio at a reference BER. This definition is directly applicable to an in-band FEC because its use implies neither an increase of the bit rate nor of the noise at the decision circuit due to receiver bandwidth expansion. The performance of an out-of-band FEC can be characterized better by a modified coding gain parameter. In wireless transmission systems the net coding gain (NCG) parameter is well established for out-of-band FEC. It takes into account the fact that the bandwidth extension needed for these FEC schemes is associated with increased noise in the receiver.

Based on the NCG value, the achievable system gain in optical signal-to-noise ratio (OSNR) limited systems can be estimated accurately. In this case, the reduction of the electrical signal-to-noise ratio as a consequence of higher line BER reflects the allowable reduction in OSNR. In systems involving additional non-white noise contributions, the trade-off between sensitivity reduction due to bandwidth expansion and coding gain is much more complicated. For comparison of high efficiency FEC schemes with different (but similar) code rates used in long-haul systems, the NCG parameter is a good measure. It should be noted, however, that this comparison is only valid in systems limited by white noise sources. In case there is a significant penalty due to (nearly deterministic) signal degradation, the penalty may increase rapidly with increasing bit rate and invalidate the comparison. Even in systems operating in a very non-linear regime of the transmission fibre, the application of NCG is of limited value due to the fact that the associated noise cannot be characterized by white Gaussian noise.

Figure 6-12 gives a performance estimation of the ITU-T G.709 FEC showing the coding gain and the net coding gain.

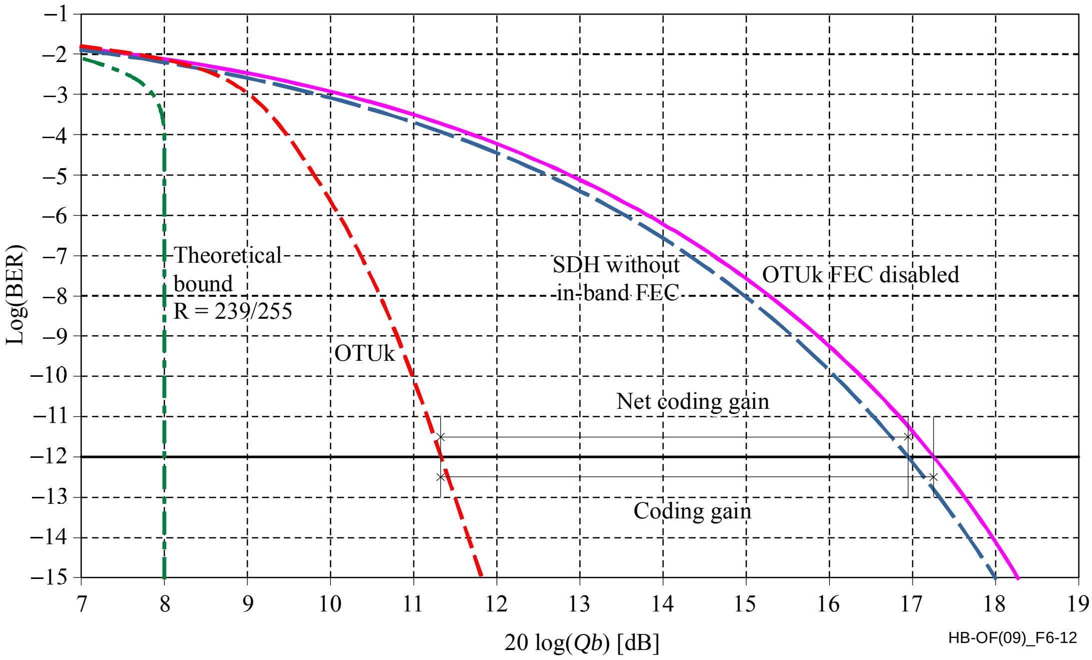

Figure 6-12 – Performance estimation of G.709 FEC

It should be noted that:

$$20\log_{10} Qb = 20\log_{10} Q - 10\log_{10} R$$

The horizontal axis is 20 $\log_{10} Qb$ in dB (see Table 6-2) and the vertical axis is Log(BER). Net coding gain in terms of 20 $\log_{10} Qb$ is equivalent to allowable OSNR reduction when the line system uses optical amplifiers and ASE induced noise is the only significant noise source at the decision circuit.

Table 6-3 gives the theoretical performance of both the above-quoted ITU-T standard FECs.

Table 6-3– Performance of standard FECs

Application	**In-band FEC** **BCH (4359,4320)**	**Out-of-band FEC** **RS (255,239)**
	SDH	**OTN**
BER_{in} for $\text{BER}_{out} = \text{BER}_{ref} = 10^{-12}$	2.9×10^{-6}	1.8×10^{-4}
Coding gain ($\text{BER}_{ref} = 10^{-12}$) (dB)	3.8	5.9
Net coding gain ($\text{BER}_{ref} = 10^{-12}$) (dB)	3.8	5.6
Code rate	1	239/255

1.13.4 Theoretical NCG bounds for some non-standard out-of-band FECs

Based on basic results from information theory, the theoretical NCG bounds, for some non-standard out-of-band FECs, as a function of code rate can be determined. Some results are shown in Table 6-4 for $BER_{ref} = 10^{-12}$.

Table 6-4 – Theoretical NCG bounds for some non-standard out-of-band FECs

Bandwidth expansion (%)	**Code rate *R***	**NCG (dB) ($BER_{ref} = 10^{-12}$)**
5	0.952	8.6
7	0.935	9.0 (Note)
10	0.909	9.4
15	0.870	9.9
20	0.833	10.3
25	0.800	10.6
NOTE – Corresponds to the code rate of standard out-of-band FEC.		

2 Objectives for standardizing optical systems

As mentioned in the introduction, the optical interfaces defined in ITU-T Recommendations are generally defined with the purpose to enable the optical interworking between the equipment from different manufacturers. Where this interworking is possible, the interfaces are called “transversely compatible” and appropriate sets of parameters and associated values are provided by the interface Recommendations. In the other cases the interfaces are called “longitudinally compatible”.

2.1 Transversely compatible and longitudinally compatible optical interfaces

(For further information see ITU-T Supplement 39 to the ITU-T G-series Recommendations).

As said above, the physical layer specifications for optical transmission systems are divided into two general types: transversely compatible and longitudinally compatible optical interfaces.

In Recommendations ITU-T G.691, ITU-T G.693, ITU-T G.695, ITU-T G.698.1, ITU-T G.698.2, ITU-T G.957 and ITU-T G.959.1, the applications are defined to be “transversely compatible”, which implies that the ends of an optical section may be terminated by equipment from different manufacturers. This is illustrated in Figure 6-13.

“Transverse Compatibility” is the capability to mix equipment of various manufacturers within a single optical transmission section. In this case each of the relevant applications is characterised by an appropriate, and unambiguous, set of optical parameters and associated parameter values, valid at the defined optical interface points.

In the example shown in Figure 6-13, a full set of parameter definitions and associated values at interface point MPI-S (multi-path interface at the source) and MPI-R (multi-path interface at the receiver) are necessary to enable such an interface.

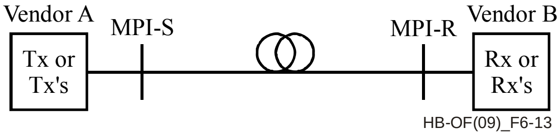

Figure 6-13 – Single-span physical layer transverse compatibility

In contrast to the above, an application that is defined to be "longitudinally compatible" implies that both ends of an optical section are terminated by equipment from the same manufacturer. The specification also allows the deployment of systems from different vendors on the optical fibres of the same cable.

In this case a more limited set of parameters than for transversely compatible systems is required, and usually only the characteristics of the optical path (e.g. attenuation, dispersion, reflections, etc.) are specified.

A single-span longitudinally compatible system is illustrated in Figure 6-14.

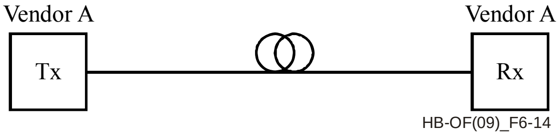

Figure 6-14 – Single-span physical layer longitudinal compatibility

For multi-span systems, longitudinal compatibility is also possible. This is similar to the single-span longitudinally compatible system, where all the active equipment comes from a single source. This is illustrated in Figure 6-15. As in the case of single span, only a limited number of parameters are required to be specified.

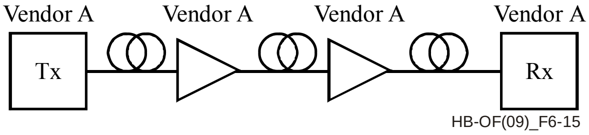

Figure 6-15 – Multi-span physical layer longitudinal compatibility

2.2 Joint engineering

(For further information see Recommendation ITU-T G.957 and Supplement 39 to the ITU-T G-series Recommendations).

In some cases the link performance provided by ITU-T Recommendations is not sufficient to cover operator needs for optical interfaces. Then, "joint engineering" can provide a means to improve the link performance to meet the specific operator requirements.

Joint engineering is a process by which operators and manufacturers jointly agree on a set of interface characteristics that support a link performance exceeding the performance available from optical interface specifications in ITU-T Recommendations. This will probably be done in those cases where the required section loss is greater (e.g. 2 dB) than that specified, but it may also be considered for other parameters.

For those cases, it is up to the operators concerned to specify more closely the aspects of the system where the specifications of the relevant Recommendation are not satisfactory. It is important to stress that every situation requiring "joint engineering" is likely to be different. Therefore, it is for the operators and/or manufacturers concerned to come to an agreement as to what is required and as to what is actually feasible. This process is very likely to lead to both ends of a transmission link being supplied by the same manufacturer, who meets the required performance by jointly optimizing the transmitters and receivers.

It should be pointed out that for "jointly engineered" systems, it would be advisable for operators or manufacturers involved to follow the general guidelines and system engineering approach used in the ITU-T Recommendations. In particular, it would be helpful to use the same parameter definitions (e.g. receiver sensitivity at R reference point including all temperature and aging effects).

2.3 Specification method: black-box and black-link

The general specification method used in ITU-T Recommendations can be categorized into two types.

The first one, the most general case, is a "black-box" approach. This means that it is not intended to restrict or specify the implementation details of the internal elements and/or the connections between the elements within the black-box.

The black-box is characterised by a set of parameters and associated values at its output (S-type interface point) and/or its input (R-type interface point). This approach enables transverse compatibility between "sending" black-box, optical link and "receiving" black-box. An example is shown in Figure 6-16 for a multi-channel interface with the multichannel interfaces points MPI-S_M and MPI-R_M.

Figure 6-16 – Black-box approach

This specification method can be used for both single-channel transmission and multi-channel transmission. It has currently been used in Recommendations ITU-T G.691, ITU-T G.692, ITU-T G.693, ITU-T G.695, ITU-T G.696.1, ITU-T G.957 and ITU-T G.959.1.

The second type is a "black-link" approach which means that optical interface parameters are specified at the single-channel interface inputs and outputs of the "black-link". The link itself is considered "black" and it may consist of passive elements (e.g. fibres, optical multiplexers, optical demultiplexers, OADMs, etc.) and active elements like optical amplifiers. The details of the black-link design are proprietary to the black-link designer. This specification method has currently been used in multi-channel transmission specified in Recommendations ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2. Additional informative descriptions are provided for the fibre link parameters of the multichannel section, such as maximum attenuation, chromatic dispersion and polarization mode dispersion. This approach enables transverse compatibility between the single-channel input and output points of a black-link. However, it does not enable transverse compatibility at the multichannel points inside the black-link. An example is shown in Figure 6-17, where the OM and OD are treated as a single set of optical devices and OADMs are also included.

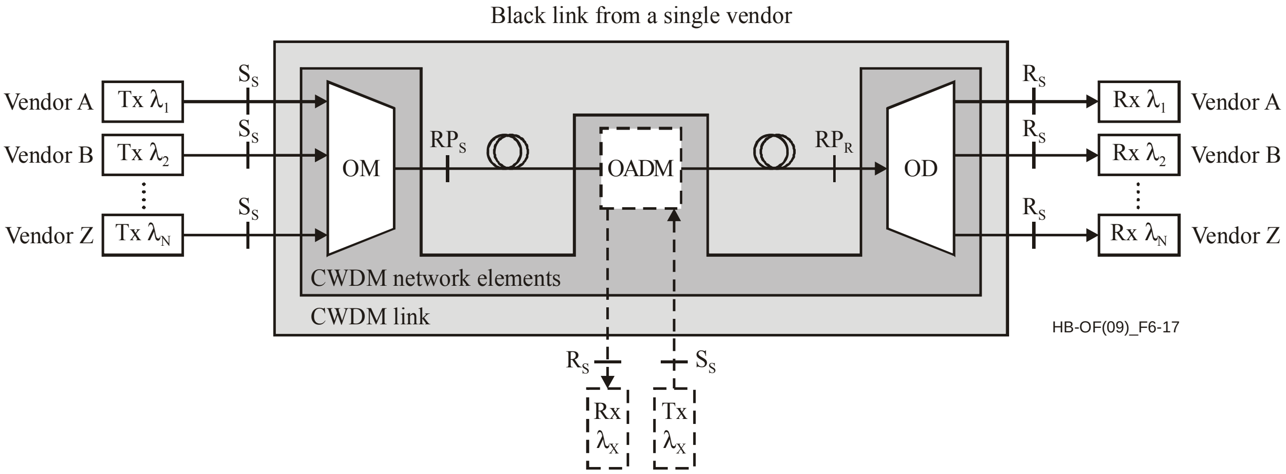

Figure 6-17 – Linear black-link approach

2.4 Application codes

For all of the Recommendations specifying optical systems, the various parameter sets in each document are termed the "applications" of the Recommendation, and each one is given its own short reference code (called the "application code"). The application codes take into account the many possible combinations of channel counts, optical tributary signal types, span distances, fibre types and system configurations.

The structure of these codes varies from one Recommendation to another, depending on the characteristics required to distinguish one application from another.

Two elements of the application code, that are common to all of the Recommendations, are an indication of the bit rate and the type of fibre over which the application operates. To illustrate how these application codes work, two examples are given. The first (Figure 6-18) is from Recommendation ITU-T G.957 which has a very simple application code structure and the second (Figure 6-19) is a more complex example from Recommendation ITU-T G.698.2.

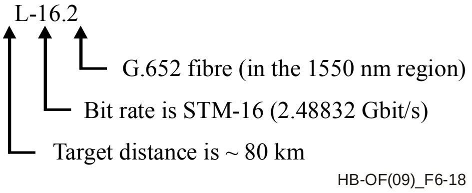

Figure 6-18 – Example of Recommendation ITU-T G.957 application code

Details of the structure and interpretation of the application codes can be found in each Recommendation.

For all the Recommendations, with the exception of those covering black-link applications, the application code includes some indication of the distance that can be covered by the link. In the example for Recommendation ITU-T G.957 in Figure 6-18, the letter L indicates a "target distance" of approximately 80 km in the 1 550 nm window, and approximately 40 km in the 1 310 nm window.

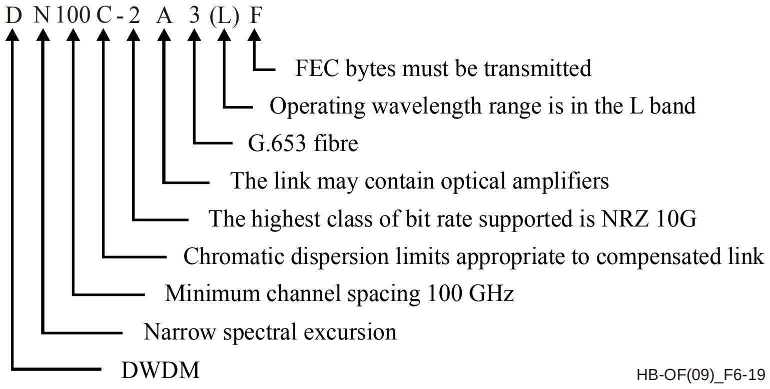

Figure 6-19 – Example of ITU-T G.698.2 application code

These target distances are for classification purposes only and do not guarantee that a link of that distance can be accommodated (or, conversely, that a link that is somewhat longer cannot). The specifications for each application code are given in terms of the maximum (and sometimes minimum) attenuation that the link must have, the limits for chromatic dispersion, the maximum reflections and (in most cases) the maximum DGD (differential group delay – a parameter related to polarisation mode dispersion) that can be tolerated.

The applications in each Recommendation do not cover all possible combinations of distance category, optical tributary signal class, and fibre type. The included applications are intended to satisfy a broad range of network requirements with low-cost implementations.

3 Parameters for the specification of the optical interfaces

Each ITU-T Recommendation has its own definition for each parameter, all being potentially slightly different in each case. To get a common basic understanding, the definitions of Recommendation ITU-T G.959.1 are used in the following.

3.1 Interface at point MPI-S and MPI-S_M

(For further information see Recommendation ITU-T G.959.1).

The interfaces MPI-S (main path interface) for a single-channel shown in Figure 6-20 and MPI-S_M for a multichannel optical system shown in Figure 6-21 are characterized by a complete set of parameters. Some of them are described in the following.

3.1.1 Output power

Two parameters specify the output power:

i) The maximum and minimum mean (*channel*) output power. The mean launched power of each optical channel at reference point MPI-S_M or MPI-S is the average power of a pseudo-random data sequence coupled into the fibre from the transmitting equipment. It is given as a range (maximum and minimum), to allow for some cost optimization and to cover allowances for operation under the standard operating conditions, connector degradations, measurement tolerances, and aging effects.

ii) The maximum mean *total* output power is the maximum value of the mean launched total optical power at point MPI-S_M.

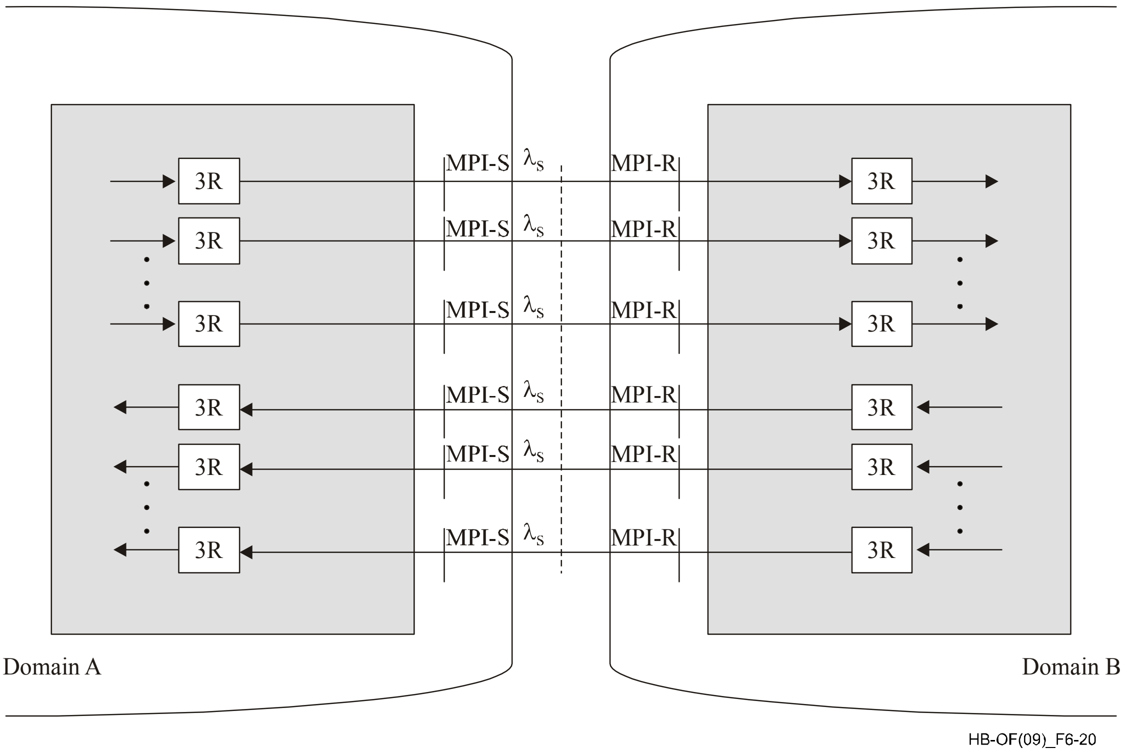

Figure 6-20 – Single-channel applications

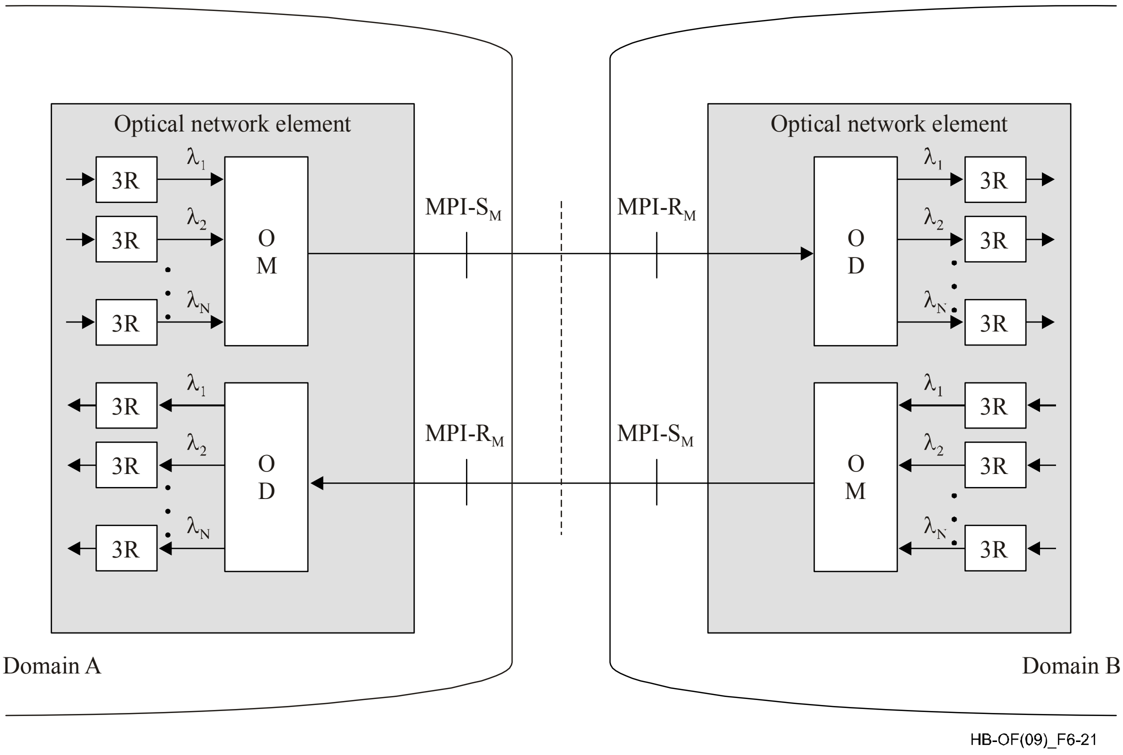

Figure 6-21 – Non-amplified multichannel applications

3.1.2 Source type

Depending on attenuation/dispersion characteristics and hierarchical level of each application codes, feasible transmitter devices use LEDs, multi-longitudinal mode (MLM) lasers and single-longitudinal mode (SLM) lasers (see Chapter 5).

For each of the applications, the Recommendations indicate a nominal source type. It is understood that the indication of a nominal source type in the Recommendation is not a requirement, so that SLM devices can be substituted for any application showing MLM as the nominal source type, without any degradation in system performance.

3.1.3 Transmitter minimum (channel) extinction ratio

Most transmitters emit some power even in the off state (logical 0 bits). The energy carried by 0 bits can be a source of power penalty in the optical receiver due to reduced eye opening. It is characterised by the parameter "transmitter extinction ratio".

The transmitter extinction ratio (EX) is defined as:

$$EX = 10 \log_{10} (A/B)$$

where:

A : average optical power level at the centre of the logical "1";

B : average optical power level at the centre of the logical "0".

The convention adopted for optical logic levels is:

- emission of light for a logical "1";
- no emission for a logical "0".

3.1.4 Eye diagram and eye mask

An indication of the quality of an optical signal can be achieved by measuring its *eye diagram* and checking whether it fits with a specified *eye mask*. In general, one could carry out this measurement at any point on the optical fibre, at the beginning (at the transmitting side), in the middle of the optical fibre path or at the end (at the receiving side). At the end of a link the optical eye contains all distortion effects encountered by transmission through the fibre (including chromatic dispersion and non-linear effects). In ITU-T Recommendations this indication of signal quality for optical interfaces is "quantified" by the definition of an eye mask for the signal at the transmitting S-type reference point.

In optical systems transmitter pulse shape characteristics (including rise time, fall time, pulse overshoot, pulse undershoot and ringing to be controlled to put limits to transmitter waveform distortion in order to prevent excessive degradation of the receiver sensitivity), are specified in the form of a mask of the transmitter eye diagram at point MPI-S. For the purpose of an assessment of the transmit signal, it is important to consider not only the eye opening, but also the overshoot and undershoot limitations.

Eye diagram. The data recovery section of optical receivers consists of a decision circuit and a clock-recovery circuit. The purpose of the latter is to isolate a spectral component at $f = B$ from the received signal. This component provides information about the bit slot ($T_B = 1/B$) to the decision circuit and helps to synchronize the decision process. In the case of RZ (return-to-zero) format, a spectral component at $f = B$ (bit frequency) is present in the received signal. In the case of NRZ (non-return-to-zero) format, a spectral component at $f = B/2$ (half bit frequency) is present in the received signal.

The decision circuit compares the output from the linear channel to a threshold level at sampling times determined by the clock recovery circuit and decides whether the signal correspond to bit value “1” or to bit value “0”. The best sampling time corresponds to the situation in which the signal level difference between 1 and 0 is maximum. This difference can be determined from the eye diagram formed by superposing 2-3 bit long electrical sequences in the bit stream on top of each other. The resulting pattern is called an eye diagram because of its appearance. Figure 6-22 shows an ideal eye diagram together with a degraded one in which the noise and the timing jitter lead to a partial closing of the eye. The best sampling time corresponds to maximum opening of the eye.

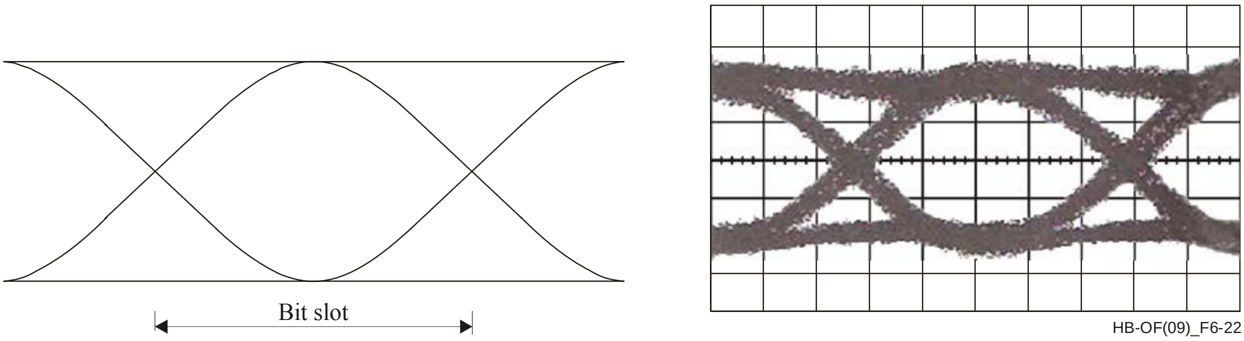

Figure 6-22 – Ideal and degraded eye mask for the NRZ format

The closure of the eye diagram at the receive side can provide the total degradation of the optical signal due to cumulative effects from the optical path.

Eye mask. The parameters specifying the mask of the transmitter eye diagram for a 2.5 Gbit/s NRZ optical transmit signals are shown in Figure 6-23. For each SDH/OTN hierarchical level optical system a different eye diagram is defined. Acceptable transmitter eye diagrams must avoid crossing any of the hatched lines. The values of x_i and y_i for the bit rate of each optical signal are specified in the relevant Recommendations.

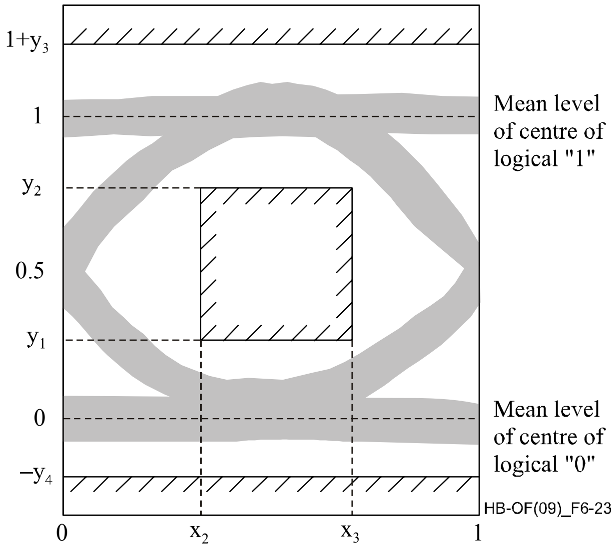

Figure 6-23 – Mask of the eye diagram for NRZ optical transmit signals

3.2 Optical path (single span MPI-S to MPI-R or MPI-S_M to MPI-R_M)

(For further information see Recommendation ITU-T G.959.1).

3.2.1 Attenuation

The minimum and maximum path attenuation is the minimum and maximum loss in dB of the optical path between transmitting, S-type, and receiving, R-type, reference points, where the system in question operates under end-of-life conditions at a BER of 10^{-12} (or as given by the application code), under worst-case, transmit-side signal.

Moreover, attenuation specifications are assumed to be worst-case values, including losses due to splices, connectors, optical attenuators (if used) or other passive optical devices and any additional cable margin to cover allowances for:

i) future modifications to the cable configuration (additional splices, increased cable lengths, etc.);

ii) fibre cable performance variations due to environmental factors;

iii) degradation of any connectors, optical attenuators or other passive optical devices involved between points MPI-S and MPI-R (if used).

Within Recommendation ITU-T G.959.1, the maximum attenuation values required are based on the assumption of 0.275 dB/km installed fibre loss (including splices and cable margin) in the 1 530-1 565 nm range, and on an assumption of a 0.55 dB/km value at 1 310 nm. From a practical point of view, attenuation spans of 11 dB for 40 km and 22 dB for 80 km at 1 550 nm and 11 dB for 20 km and 22 dB for 40 km at 1 310 nm are defined. It should be noted that this method, gives a theoretical value of span distance. In black-link based ITU-T Recommendations, like ITU-T G.695, ITU-T G.698.1 and ITU-T G.698.2, other assumptions are made for link-loss calculations.

3.2.2 Maximum chromatic dispersion at upper and lower wavelength limit

In Recommendation ITU-T G.959.1 the maximum chromatic dispersion at upper and lower wavelength limit is used to define the maximum uncompensated value of the main path chromatic dispersion that the system shall be able to tolerate. For wavelengths between the upper and lower of the wavelength range adopted, the maximum dispersion is linearly interpolated between the values given for the extreme wavelengths.

Furthermore, in Recommendation ITU-T G.959.1 the required maximum dispersion tolerance at the upper and lower wavelength limits is set to a value equal to 1.05 times the theoretical chromatic dispersion value appropriate for the target distance. These dispersion values are considered a practical upper limit for field deployments with distances at about the relevant target distances.

3.2.3 Reflections

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:

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

ii) the maximum discrete reflectance between transmitting S-type and receiving R-type reference points. Reflectance denotes the reflection from any single discrete reflection point. 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.

The maximum number of connectors or other discrete reflection points that 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 requested in the Recommendations, then connectors having better reflection performance must be employed. Alternatively, the number of connectors must be reduced. It also may 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.

3.2.4 Maximum differential group delay

Differential group delay (DGD) is the time difference between the fractions of a pulse that are transmitted in the two principal states of polarization of an optical signal. For distances greater than several kilometres, and assuming random (strong) polarization mode coupling, DGD in a fibre can be statistically modelled as having a Maxwellian distribution (see Chapter 1).

The maximum differential group delay is defined to be the value of DGD that the system must tolerate with a maximum sensitivity degradation of approximately 1 dB.

Due to the statistical nature of polarization mode dispersion (PMD), the relationship between maximum DGD and mean DGD can only be defined probabilistically. The probability of the instantaneous DGD exceeding any given value can be inferred from its Maxwellian statistics. Therefore, if we know the maximum DGD that the system can tolerate, we can derive the equivalent mean DGD by dividing by the ratio of maximum to mean that corresponds to an acceptable probability. Some example ratios are given below in Table 6-5.

Table 6-5 – DGD means and probabilities

Ratio of maximum to mean	Probability of exceeding maximum
3.0	4.2×10^{-5}
3.5	7.7×10^{-7}
4.0	7.4×10^{-9}

3.3 Interface at point MPI-R_M and MPI-R

(For further information see Recommendation ITU-T G.959.1).

3.3.1 Input power

The following parameters specify the input power:

i) *maximum mean channel input power*, which is the maximum acceptable value of the average received channel power at point MPI-R_M or MPI-R to achieve the specified maximum BER of the application code;

ii) *minimum mean channel input power*, which is the minimum value of the average received channel power at point MPI-R_M. This power is the minimum mean channel output power minus the maximum attenuation of the application;

iii) *maximum mean total input power*, relevant only in the case of multi-channel operation, which is the maximum acceptable total input power at point MPI-R_M.

3.3.2 Minimum receiver sensitivity

In general the minimum receiver sensitivity is the minimum value of average received power at point MPI-R (single-channel interface) to achieve the specified maximum BER of the application code. In most cases the minimum receiver sensitivity is specified at a BER of 10^{-12}, except in Recommendation ITU-T G.957 applications where a reference BER of 10^{-10} is defined. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at points MPI-S, connector degradations, optical amplifier noise, and measurement tolerances. This does not have to be met in the presence of dispersion or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

3.3.3 Minimum equivalent sensitivity

This is the minimum sensitivity that would be required by a receiver placed at MPI-R_M (multichannel interfaces) to achieve the specified maximum BER of the application code, if all except one of the channels were to be removed (with an ideal loss-less filter) at point MPI-R_M. This must be met with a transmitter with worst-case values of transmitter eye mask, extinction ratio, optical return loss at point MPI-S_M, connector degradations, transmit-side crosstalk, optical amplifier noise, and measurement tolerances. This does not have to be met in the presence of dispersion, non-linearity, or reflections from the optical path; these effects are specified separately in the allocation of maximum optical path penalty.

3.3.4 Maximum optical path penalty

Within Recommendation ITU-T G.959.1 the path penalty is defined as the apparent reduction of receiver sensitivity (or equivalent sensitivity in the case of multichannel applications) due to distortion of the signal waveform during its transmission over the path. It is manifested as a shift of the system's BER-curves towards higher input power levels. This corresponds to a positive path penalty. Negative path penalties may exist under some circumstances, but are generally expected to be sufficiently small. Ideally, the BER-curves should be shifted only towards higher receiver input power levels, but shape variations of the BER-curves are not uncommon. Within Recommendation ITU-T G.959.1 the path penalty is defined at a BER-level of 10^{-12}.

For application codes requiring FEC bytes to be transmitted, both receiver sensitivities (with and without the degradation due to the optical path) are measured after the error correction has been applied.

For Recommendation ITU-T G.959.1 applications with channel bit rates corresponding to NRZ 2.5G and NRZ 10G, a maximum path penalty of 1 dB or 2 dB is defined. The actual value depends on the application and on the fibre type (Recommendations ITU-T G.652, ITU-T G.653 and ITU-T G.655). The path penalties are not made proportional to the target distances to avoid operating systems with high penalties.

Power penalties associated with the optical path (like chromatic fibre dispersion or polarization-mode dispersion, jitter, reflections) are contained in the maximum optical path penalty, but not in the minimum receiver sensitivity. As a consequence the maximum optical path attenuation is the difference between minimum transmitter output power and the minimum receiver sensitivity additionally reduced by the value of the optical path penalty (Figure 6-24).

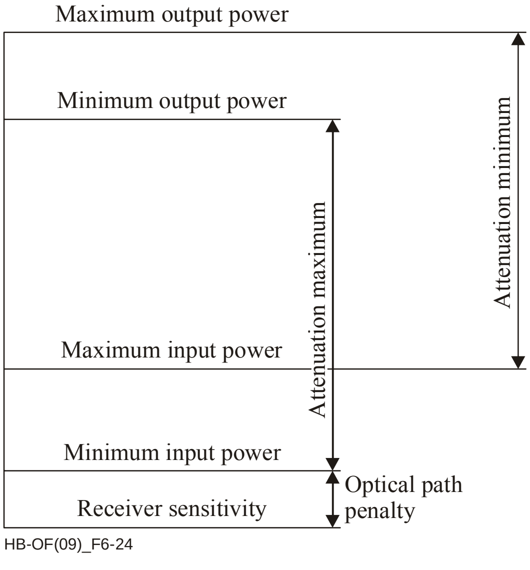

Figure 6-24 – Relationship of the optical parameters in a single-channel system

4 Example of an optical interface specification

Table 6-6 contains an example of specification for an optical system taken from Recommendation ITU-T G.959.1.

It refers to a single-span DWDM system with 32 channels operating at 10 Gbit/s in the C-band on ITU-T G.652 fibres.

Table 6-6 – Example of a multi-channel optical interface specification

Parameter (Note)	Units	
General information		
Maximum number of channels	–	32
Bit rate/line coding of optical tributary signals	–	NRZ 10G
Maximum bit error ratio	–	10^{-12}
Fibre type	–	G.652
Interface at point MPI-S_M		
Maximum mean channel output power	dBm	+3
Minimum mean channel output power	dBm	0
Maximum mean total output power	dBm	+18
Central frequency	THz	192.1 + 0.1 m, m = 0 to 31
Channel spacing	GHz	100
Maximum spectral excursion	GHz	20
Minimum channel extinction ratio	dB	8.2
Eye mask	–	NRZ 10G amplified
Optical path (single span) from point MPI-S_M to MPI-R_M		
Maximum attenuation	dB	11
Minimum attenuation	dB	0
Maximum chromatic dispersion at upper wavelength limit	ps/nm	800 for the G.652 fibre
Maximum chromatic dispersion at lower wavelength limit	ps/nm	800 for the G.652 fibre
Minimum optical return loss at MPI-S_M	dB	24
Maximum discrete reflectance between MPI-S_M and MPI-R_M	dB	–27
Maximum differential group delay	ps	30
Interface at point MPI-R_M		
Maximum mean channel input power	dBm	+3
Minimum mean channel input power	dBm	–11
Maximum mean total input power	dBm	+18
Maximum channel power difference	dB	NA
Maximum optical path penalty	dB	2
Minimum equivalent sensitivity	dBm	–13 for ITU-T G.652 fibre
Maximum reflectance of optical network element	dB	–27

The parameters quoted in Table 6-6 with their values (relevant for the specific optical system) are those listed in the above § 3.