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Transmission media characteristics – Optical fibre cables

Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable

ITU-T Recommendation G.655

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TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

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ITU-T Recommendation G.655

Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable

Summary

This Recommendation describes the geometrical, mechanical, and transmission attributes of a single-mode optical fibre which has the absolute value of the chromatic dispersion coefficient greater than some non-zero value throughout the wavelength range from 1530 nm to 1565 nm. This dispersion reduces the growth of non-linear effects which are particularly deleterious in dense wavelength division multiplexing systems. This is the latest revision of a Recommendation that was first created in 1996. This revision adds two new categories of this fibre in Tables D and E. Both of these categories limit the chromatic dispersion coefficient by a pair of bounding curves vs wavelength for the range of 1460 nm to 1625 nm. Although the dispersion can change sign at wavelengths less than 1530 nm, the inclusion of these lower wavelengths is intended to provide information to support coarse wavelength division multiplexing applications which do not have significant non-linear impairments, at channels from 1471 nm and higher. These tables are introduced to distinguish the two main families of G.655 fibres that are supported by multiple vendors. Tables A, B, and C have not been changed. Tables A and B are not included in this version of this Recommendation, but are in the 2003 edition.

Source

ITU-T Recommendation G.655 was approved on 29 March 2006 by ITU-T Study Group 15 (2005-2008) under the ITU-T Recommendation A.8 procedure.

1996 First version.

10/2000 Version 2. This revision includes the addition of tables for different levels of system support.

03/2003 Version 3. In accordance with the agreement on spectral bands, the description of the L band upper limit is changed from 16xx to 1625 nm. Terms of base subcategory and subcategory are revised to base category and category, respectively. PMD requirements are added for all categories and two categories have reduced limits (compared to 0.5 ps/√km). For the macrobending test, mandrel diameter is reduced to 30 mm radius. As seen above, this Recommendation has evolved considerably over the years; therefore, the reader is warned to consider the appropriate version to determine the characteristics of an already deployed product, taking into account the year of production. In fact, products are expected to comply with the Recommendation that was in force at the time of their manufacture, but may not fully comply with subsequent versions of the Recommendation.

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NOTE

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

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As of the date of approval of this Recommendation, ITU had received notice of intellectual property, protected by patents, which may be required to implement this Recommendation. However, implementors are cautioned that this may not represent the latest information and are therefore strongly urged to consult the TSB patent database.

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ITU-T Recommendation G.655

Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable

1 Scope

This Recommendation describes a single-mode fibre with chromatic dispersion coefficient (absolute value) that is greater than some non-zero value throughout the wavelengths larger than 1530 nm. This dispersion reduces the growth of non-linear effects that can be particularly deleterious in Dense Wavelength Division Multiplexing (DWDM) systems. At lower wavelengths, the dispersion coefficient can cross zero, but chromatic dispersion coefficient values at these wavelengths may be specified to support Coarse Wavelength Division Multiplexing (CWDM) systems that do not have significant impairments due to non-linear effects.

These fibres were originally intended for use at wavelengths in a prescribed region between 1530 nm and 1565 nm. Provisions have been made to support transmission at higher wavelengths of up to 1625 nm and lower wavelengths down to 1460 nm.

In clause 7, Tables D and E distinguish the two main families of G.655 fibre implementations that are supported by multiple vendors. Tables A, B, and C can be used to define other implementations. Tables A and B are not included in this publication but are found in the 2003 edition of this Recommendation.

The geometrical, optical, transmission and mechanical parameters are described below in three categories of attributes:

- fibre attributes are those attributes that are retained throughout cabling and installation;
- cable attributes that are recommended for cables as they are delivered;
- link attributes that are characteristics of concatenated cables, describing estimation methods of system interface parameters based on measurements, modelling, or other considerations. Information for link attributes and system design are in Appendix I.

This Recommendation, and the different performance categories found in the tables of clause 7, is intended to support the following related system Recommendations:

- ITU-T Rec. G.691;
- ITU-T Rec. G.692;
- ITU-T Rec. G.693;
- ITU-T Rec. G.695;
- ITU-T Rec. G.696.1;
- ITU-T Rec. G.698.1;
- ITU-T Rec. G.957;
- ITU-T Rec. G.959.1.

This Recommendation contains a combination of fibre designs able to cover a broad spectrum of applications. Some re-arrangement might be considered in the future. However, the system compatibility of fibres with different characteristics is not proved and, in general, their simultaneous use in one system might be questioned and should be agreed in advance between the user and manufacturers.

The meaning of the terms used in this Recommendation and the guidelines to be followed in the measurement to verify the various characteristics are given in ITU-T Recs G.650.1 and G.650.2. The characteristics of this fibre, including the definitions of the relevant parameters, their test methods and relevant values, will be refined as studies and experience progress.

2 References

2.1 Normative references

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

– ITU-T Recommendation G.650.1 (2004), *Definitions and test methods for linear, deterministic attributes of single-mode fibre and cable*.

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

2.2 Informative references

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

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

– ITU-T Recommendation G.692 (1998), *Optical interfaces for multichannel systems with optical amplifiers*.

– ITU-T Recommendation G.693 (2006), *Optical interfaces for intra-office systems*.

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

– ITU-T Recommendation G.695 (2005), *Optical interfaces for coarse wavelength division multiplexing applications*.

– ITU-T Recommendation G.696.1 (2005), *Longitudinally compatible intra-domain DWDM applications*.

– ITU-T Recommendation G.698.1 (2005), *Multichannel DWDM applications with single-channel optical interfaces*.

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

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

3 Terms and definitions

For the purposes of this Recommendation, the definitions given in ITU-T Recs G.650.1 and G.650.2 apply. Values shall be rounded to the number of digits given in the tables of recommended values before conformance is evaluated.

4 Abbreviations

This Recommendation uses the following abbreviations:

A_{eff}	Effective Area
CWDM	Coarse Wavelength Division Multiplexing
DGD	Differential Group Delay
DWDM	Dense Wavelength Division Multiplexing
GPa	GigaPascal
PMD	Polarization Mode Dispersion
PMD_Q	Statistical Parameter for PMD link
SDH	Synchronous Digital Hierarchy
TBD	To Be Determined
WDM	Wavelength Division Multiplexing

5 Fibre attributes

Only those characteristics of the fibre providing a minimum essential design framework for fibre manufacturers are recommended in this clause. Ranges or limits on values are presented in the tables of clause 7. Of these, cable manufacture or installation may significantly affect the cabled fibre cut-off wavelength and PMD. Otherwise, the recommended characteristics will apply equally to individual fibres, fibres incorporated into a cable wound on a drum, and fibres in an installed cable.

5.1 Mode field diameter

Both a nominal value and tolerance about that nominal value shall be specified at 1550 nm. The nominal that is specified shall be within the range found in clause 7. The specified tolerance shall not exceed the value in clause 7. The deviation from nominal shall not exceed the specified tolerance.

5.2 Cladding diameter

The recommended nominal value of the cladding diameter is 125 μm. A tolerance is also specified and shall not exceed the value in clause 7. The cladding deviation from nominal shall not exceed the specified tolerance.

5.3 Core concentricity error

The core concentricity error shall not exceed the value specified in clause 7.

5.4 Non-circularity

5.4.1 Mode field non-circularity

In practice, the mode field non-circularity of fibres having nominally circular mode fields is found to be sufficiently low that propagation and jointing are not affected. It is, therefore, not considered necessary to recommend a particular value for the mode field non-circularity. It is not normally necessary to measure the mode field non-circularity for acceptance purposes.

5.4.2 Cladding non-circularity

The cladding non-circularity shall not exceed the value found in clause 7.

5.5 Cut-off wavelength

Three useful types of cut-off wavelength can be distinguished:

a) Cable cut-off wavelength, λ_{cc}.

b) Fibre cut-off wavelength, λ_c.

c) Jumper cable cut-off wavelength, λ_{cj}.

NOTE – For some specific submarine cable applications, other cable cut-off wavelength values may be required.

The correlation of the measured values of λ_c, λ_{cc}, and λ_{cj} depends on the specific fibre and cable design and the test conditions. While in general, $\lambda_{cc} < \lambda_{cj} < \lambda_c$, a general quantitative relationship cannot be easily established. The importance of ensuring single-mode transmission in the minimum cable length between joints, at the minimum operating wavelength, is paramount. This may be performed by recommending the maximum cable cut-off wavelength λ_{cc} of a cabled single-mode fibre to be 1480 nm, or for typical jumpers by recommending a maximum jumper cable cut-off to be 1480 nm, or, for worst-case length and bends, by recommending a maximum fibre cut-off wavelength to be 1470 nm.

The cable cut-off wavelength, λ_{cc}, shall be less than the maximum specified in clause 7.

5.6 Macrobending loss

Macrobending loss varies with wavelength, bend radius and number of turns about a mandrel with a specified radius. Macrobending loss shall not exceed the maximum given in clause 7 for the specified wavelength(s), bend radius, and number of turns.

NOTE 1 – A qualification test may be sufficient to ensure that this requirement is being met.

NOTE 2 – The recommended number of turns corresponds to the approximate number of turns deployed in all splice cases of a typical repeater span. The recommended radius is equivalent to the minimum bend-radius widely accepted for long-term deployment of fibres in practical systems installations to avoid static-fatigue failure.

NOTE 3 – If, for practical reasons, fewer than the recommended number of turns are chosen to be implemented, it is suggested that not less than 40 turns, and a proportionately smaller loss increase be required.

NOTE 4 – The macrobending loss recommendation relates to the deployment of fibres in practical single-mode fibre installations. The influence of the stranding-related bending radii of cabled single-mode fibres on the loss performance is included in the loss specification of the cabled fibre.

NOTE 5 – In the event that routine tests are required, a smaller diameter loop with one or several turns can be used instead of the recommended test, for accuracy and measurement ease. In this case, the loop diameter, number of turns, and the maximum permissible bend loss for the several-turn test should be chosen so as to correlate with the recommended test and allowed loss.

5.7 Material properties of the fibre

5.7.1 Fibre materials

The substances of which the fibres are made should be indicated.

NOTE – Care may be needed in fusion splicing fibres of different substances. Provisional results indicate that adequate splice loss and strength can be achieved when splicing different high-silica fibres.

5.7.2 Protective materials

The physical and chemical properties of the material used for the fibre primary coating and the best way of removing it (if necessary) should be indicated. In the case of single jacketed fibre, similar indications shall be given.

5.7.3 Proofstress level

The specified proofstress, σ_p, shall not be less than the minimum specified in clause 7.

NOTE – The definitions of the mechanical parameters are contained in 3.2.3/G.650.1 and 5.6/G.650.1.

5.8 Refractive index profile

The refractive index profile of the fibre does not generally need to be known.

5.9 Longitudinal uniformity of chromatic dispersion

Under study.

NOTE – At a particular wavelength, the local absolute value of chromatic dispersion coefficient can vary away from the value measured on a long length. If the value decreases to a small value at a wavelength that is close to an operating wavelength in a WDM system, four-wave mixing can induce the propagation of power at other wavelengths, including, but not limited to, other operating wavelengths. The magnitude of the four-wave mixing power is a function of the absolute value of chromatic dispersion coefficient, the chromatic dispersion slope, the operating wavelengths, the optical power, and the distance over which four-wave mixing occurs.

5.10 Chromatic dispersion coefficient

The chromatic dispersion coefficient, *D*, is specified with a wavelength range. ITU-T Rec. G.650.1 provides measurement methods. There are two methods for specifying the limits, the original method, which is a box-like specification, and a newer method, in which the dispersion coefficient values are bound by a pair of curves.

NOTE 1 – Chromatic dispersion uniformity should be consistent with the functioning of the system.

NOTE 2 – The requirements on chromatic dispersion follow from WDM system design, which must balance first order chromatic dispersion with various non-linear effects, such as four-wave mixing, cross-phase modulation, modulation instability, stimulated Brillouin scattering, and soliton formation (see ITU-T Rec. G.663). The effect of chromatic dispersion is interactive with the fibre non-linearity, described by the non-linear coefficient.

NOTE 3 – It is not necessary to measure the chromatic dispersion coefficient on a routine basis.

5.10.1 Original specification form

This specification form applies to Table C in clause 7, as well as Tables A and B from the 2003 version of this Recommendation.

The chromatic dispersion coefficient, *D*, is specified within a wavelength range by stating a range of allowed absolute values of the chromatic dispersion coefficient. The chromatic dispersion coefficient shall not cross zero within the specified wavelength range. The sign of the chromatic dispersion is also specified. The form of the specification is:

$$D_{min} \le |D(\lambda)| \le D_{max} \qquad \text{for } \lambda_{min} \le \lambda \le \lambda_{max}$$

where:

$$0.1 \text{ ps/nm·km} \le D_{min} \le D_{max} \le 10.0 \text{ ps/nm·km}$$

$$1530 \text{ nm} \le \lambda_{min} \le \lambda_{max} \le 1565 \text{ nm}$$

$$D_{max} \le D_{min} + 5.0 \text{ ps/nm·km}$$

Values for D_{min}, D_{max}, λ_{min}, λ_{max}, and sign shall be within the ranges given in clause 7. Some examples of implementation are given in Appendix I. Extension to wavelength ranges above 1565 nm and below 1530 nm are under consideration.

NOTE 1 – D_{min} does not necessarily occur at λ_{min} and D_{max} does not necessarily occur at λ_{max}.

NOTE 2 – The sign of D does not change over the above wavelength range for a given fibre, but it may change from one fibre to another within a system.

NOTE 3 – Depending on the system design and transmission type, it may be necessary to specify the sign of D.

5.10.2 Specification based on a pair of limiting curves

This specification form applies to Tables D and E of clause 7.

For each wavelength, λ, the chromatic dispersion coefficient, $D(\lambda)$, shall be restricted to a range of values associated with two limiting curves, $D_{min}(\lambda)$ and $D_{max}(\lambda)$, for one or more specified wavelength ranges defined in terms of λ_{min} and λ_{max}.

An example set of curves is represented symbolically as a pair of straight lines:

$$D_{min}(\lambda) = a_{min} + b_{min}(\lambda - 1460) \quad \text{(ps/nm·km)}$$

$$D_{max}(\lambda) = a_{max} + b_{max}(\lambda - 1460) \quad \text{(ps/nm·km)}$$

$$D_{min}(\lambda) \leq D(\lambda) \leq D_{max}(\lambda) \quad \text{(ps/nm·km)}$$

The bounding curves may vary from one wavelength range to another.

6 Cable attributes

Since the geometrical and optical characteristics of fibres given in clause 5 are barely affected by the cabling process, this clause will give recommendations mainly relevant to transmission characteristics of cabled factory lengths. Environmental and test conditions are paramount and are described in the guidelines for test methods.

6.1 Attenuation coefficient

The attenuation coefficient is specified with a maximum value at one or more wavelengths in the 1550 nm region. The optical fibre cable attenuation coefficient values shall not exceed the values found in clause 7.

NOTE – The attenuation coefficient may be calculated across a spectrum of wavelengths, based on measurements at a few (3 to 4) predictor wavelengths. This procedure is described in 5.4.4/G.650.1 and an example is given in Appendix III/G.650.1.

6.2 Polarization Mode Dispersion (PMD) coefficient

When required, cabled fibre polarization mode dispersion shall be specified on a statistical basis, not on an individual fibre basis. The requirements pertain only to the aspect of the link calculated from cable information. The metrics of the statistical specification are found below. Methods of calculations are found in IEC/TR 61282-3 and are summarized in Appendix IV/G.650.2.

The manufacturer shall supply a PMD link design value, PMD_Q, that serves as a statistical upper bound for the PMD coefficient of the concatenated optical fibre cables within a defined possible link of M cable sections. The upper bound is defined in terms of a small probability level, Q, which is the probability that a concatenated PMD coefficient value exceeds PMD_Q. For the values of M and Q given in clause 7, the value of PMD_Q shall not exceed the maximum PMD coefficient specified in clause 7.

Measurements and specifications on uncabled fibre are necessary, but not sufficient to ensure the cabled fibre specification. The maximum link design value specified on uncabled fibre shall be less than or equal to that specified for the cabled fibre. The ratio of PMD values for uncabled fibre to cabled fibre depends on the details of the cable construction and processing, as well as on the mode coupling condition of the uncabled fibre. ITU-T Rec. G.650.2 recommends a low mode coupling deployment requiring a low tension wrap on a large diameter spool for uncabled fibre PMD measurements.

The limits on the distribution of PMD coefficient values can be interpreted as being nearly equivalent to limits on the statistical variation of the differential group delay (DGD), that varies randomly with time and wavelength. When the PMD coefficient distribution is specified for optical fibre cable, equivalent limits on the variation of DGD can be determined. The metrics and values for link DGD distribution limits are found in Appendix I.

NOTE 1 – PMD_Q specification would be required only where cables are employed for systems that have the specification of the max DGD, i.e., for example, PMD_Q specification would not be applied to systems recommended in ITU-T Rec. G.957.

NOTE 2 – PMD_Q should be calculated for various types of cables, and they should usually be calculated using sampled PMD values. The samples would be taken from cables of similar construction.

NOTE 3 – The PMD_Q specification should not be applied to short cables such as jumper cables, indoor cables and drop cables.

7 Tables of recommended values

The following tables summarize the recommended values for a number of categories of fibres that satisfy the objectives of this Recommendation. These categories are largely distinguished on the basis of PMD requirements and chromatic dispersion characteristics. See Appendix I for information about transmission distances and bit-rates relative to PMD requirements.

Table 1, "G.655.A Attribute" and Table 2, "G.655.B Attribute" are found in the 2003 version of this Recommendation.

Table 3, "G.655.C Attribute", retains the original "box-type" specification for the dispersion coefficient, which allows a reference to negative dispersion fibres that may be suitable as part of dispersion managed links such as those that may be used in submarine systems. This also supports optical interface Recommendations such as ITU-T Recs G.691, G.959.1 and G.693. For DWDM systems, channel spacings defined in ITU-T Rec. G.694.1 are supported, depending on the minimum dispersion that is selected. The PMD requirement allows operation of STM-64 systems to lengths of up to 2000 km, depending on other system elements.

Table 4, "G.655.D Attribute", defines the chromatic dispersion coefficient requirements as a pair of bounding curves vs wavelength for wavelengths from 1460 nm to 1625 nm. For wavelengths greater than 1530 nm, the dispersion is positive and of sufficient magnitude to suppress most non-linear impairments. For these wavelengths, the applications mentioned in Table 3 are supported. For wavelengths less than 1530 nm, the dispersion crosses zero, but the fibre can be used to support CWDM applications at channels from 1471 nm and higher.

Table 5, "G.655.E Attribute", defines the chromatic dispersion requirements in the same style as Table 4, but has higher values which can be important for some systems, e.g., for those with the smallest channel spacings. The applications mentioned in Table 3 are supported. Fibres meeting these requirements are positive and non-zero at wavelengths above 1460 nm.

NOTE – Many submarine applications can utilize these fibres. For some submarine applications, the full optimization can lead to choosing different limits than are found here. One example could be to allow cable cut-off wavelength values as high as 1500 nm.

Appendix I illustrates various implementation examples that are differentiated on the basis of different chromatic dispersion values, dispersion slope, and different non-linear coefficient link values. These options illustrate possibilities for different tradeoffs between power, channel spacing, link length, amplifier spacing, and bit rate.

Table 3/G.655 – G.655.C attributes

Fibre attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1550 nm
	Range of nominal values	8-11 μm
	Tolerance	± 0.7 μm
Cladding diameter	Nominal	125 μm
	Tolerance	± 1 μm
Core concentricity error	Maximum	0.8 μm
Cladding non-circularity	Maximum	2.0%
Cable cut-off wavelength	Maximum	1450 nm
Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.50 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient Wavelength range: 1530-1565 nm	λ_{min} and λ_{max}	1530 nm and 1565 nm
	Minimum value of D_{min}	1.0 ps/nm·km
	Maximum value of D_{max}	10.0 ps/nm·km
	Sign	Positive or negative
	$D_{max} - D_{min}$	≤ 5.0 ps/nm·km
Chromatic dispersion coefficient Wavelength range: 1565-1625 nm	λ_{min} and λ_{max}	TBD
	Minimum value of D_{min}	TBD
	Maximum value of D_{max}	TBD
	Sign	Positive or negative
Uncabled fibre PMD coefficient	Maximum	(see Note 1)
Cable attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum at 1550 nm	0.35 dB/km
	Maximum at 1625 nm	0.4 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMD_Q	0.20 ps/√km
NOTE 1 – According to 6.2, a maximum PMD_Q value on uncabled fibre is specified in order to support the primary requirement on cable PMD_Q. NOTE 2 – Larger PMD_Q values (e.g., ≤ 0.5 ps/√km) can be agreed for particular applications between the manufacturer and user.		

Table 4/G.655 – G.655.D attributes

Fibre attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1550 nm
	Range of nominal values	8-11 µm
	Tolerance	± 0.6 µm
Cladding diameter	Nominal	125 µm
	Tolerance	± 1 µm
Core concentricity error	Maximum	0.6 µm
Cladding non-circularity	Maximum	1.0%
Cable cut-off wavelength	Maximum	1450 nm
Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.1 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient (ps/nm·km)	$D_{min}(\lambda)$: 1460-1550 nm	$\frac{7.00}{90}(\lambda - 1460) - 4.20$
	$D_{min}(\lambda)$: 1550-1625 nm	$\frac{2.97}{75}(\lambda - 1550) + 2.80$
	$D_{max}(\lambda)$: 1460-1550 nm	$\frac{2.91}{90}(\lambda - 1460) + 3.29$
	$D_{max}(\lambda)$: 1550-1625 nm	$\frac{5.06}{75}(\lambda - 1550) + 6.20$
Cable attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum at 1550 nm	0.35 dB/km
	Maximum at 1625 nm	0.4 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMD_Q	0.20 ps/√km
NOTE 1 – According to 6.2, a maximum PMD_Q value on uncabled fibre is specified in order to support the primary requirement on cable PMD_Q. NOTE 2 – Larger PMD_Q values (e.g., ≤ 0.5 ps/√km) can be agreed for particular applications between the manufacturer and user.		

Table 5/G.655 – G.655.E attributes

Fibre attributes		
Attribute	**Detail**	**Value**
Mode field diameter	Wavelength	1550 nm
	Range of nominal values	8-11 µm
	Tolerance	± 0.6 µm
Cladding diameter	Nominal	125 µm
	Tolerance	± 1 µm
Core concentricity error	Maximum	0.6 µm
Cladding non-circularity	Maximum	1.0%
Cable cut-off wavelength	Maximum	1450 nm
Macrobend loss	Radius	30 mm
	Number of turns	100
	Maximum at 1625 nm	0.1 dB
Proof stress	Minimum	0.69 GPa
Chromatic dispersion coefficient (ps/nm·km)	$D_{min}(\lambda)$: 1460-1550 nm	$\frac{5.42}{90}(\lambda-1460)+0.64$
	$D_{min}(\lambda)$: 1550-1625 nm	$\frac{3.30}{75}(\lambda-1550)+6.06$
	$D_{max}(\lambda)$: 1460-1550 nm	$\frac{4.65}{90}(\lambda-1460)+4.66$
	$D_{max}(\lambda)$: 1550-1625 nm	$\frac{4.12}{75}(\lambda-1550)+9.31$
Cable attributes		
Attribute	**Detail**	**Value**
Attenuation coefficient	Maximum at 1550 nm	0.35 dB/km
	Maximum at 1625 nm	0.4 dB/km
PMD coefficient	M	20 cables
	Q	0.01%
	Maximum PMD_Q	0.20 ps/√km
NOTE 1 – According to 6.2, a maximum PMD_Q value on uncabled fibre is specified in order to support the primary requirement on cable PMD_Q.		
NOTE 2 – Larger PMD_Q values (e.g., ≤ 0.5 ps/√km) can be agreed for particular applications between the manufacturer and user.		

Appendix I

Information for link attributes and system design

A concatenated link usually includes a number of spliced factory lengths of optical fibre cable. The requirements for factory lengths are given in clauses 5 and 6. The transmission parameters for concatenated links must take into account not only the performance of the individual cable lengths but also the statistics of concatenation.

The transmission characteristics of the factory length optical fibre cables will have a certain probability distribution which often needs to be taken into account if the most economic designs are to be obtained. The following clauses should be read with this statistical nature of the various parameters in mind.

Link attributes are affected by factors other than optical fibre cables by such things as splices, connectors, and installation. These factors cannot be specified in this Recommendation. For the purpose of link attribute values estimation, typical values of optical fibre links are provided in I.5. Clause I.6 contains examples of implementation where the typical values of chromatic dispersion vary from example to example. The estimation methods of parameters needed for system design are based on measurements, modelling, or other considerations.

I.1 Attenuation

The attenuation A of a link is given by:

$$A = \alpha L + \alpha_s x + \alpha_c y$$

where:

- α typical attenuation coefficient of fibre cables in a link
- α_s mean splice loss
- x number of splices in a link
- α_c mean loss of line connectors
- y number of line connectors in a link (if provided)
- L link length

A suitable margin should be allocated for future modifications of cable configurations (additional splices, extra cable lengths, ageing effects, temperature variations, etc.). The above equation does not include the loss of equipment connectors. The typical values found in I.5 are for the attenuation coefficient of optical fibre links. The attenuation budget used in designing an actual system should account for the statistical variations in these parameters.

I.2 Chromatic dispersion

The chromatic dispersion in ps/nm can be calculated from the chromatic dispersion coefficients of the factory lengths, assuming a linear dependence on length, and with due regard for the signs of the coefficients (see 5.10).

When these fibres are used for transmission in the 1550 nm region, chromatic dispersion accommodation is sometimes employed. In this case, the average link chromatic dispersion is used for design. The relationship is described in terms of the typical chromatic dispersion coefficient and chromatic dispersion slope coefficient at 1550 nm.

Typical values for the chromatic dispersion coefficient, D_{1550}, and chromatic dispersion slope coefficient, S_{1550}, at 1550 nm vary with the specific implementation. Values may be found in I.6 for the examples given. These values, together with link length, L_{Link}, can be used to calculate the typical dispersion for use in optical link design.

$$D_{Link}(\lambda) = L_{Link}\left[D_{1550} + S_{1550}(\lambda - 1550)\right] \quad (ps/nm)$$

I.3 Differential group delay (DGD)

The differential group delay is the difference in arrival times of the two polarization modes at a particular wavelength and time. For a link with a specific PMD coefficient, the DGD of the link varies randomly with time and wavelength as a Maxwell distribution that contains a single parameter which is the product of the PMD coefficient of the link and the square root of the link length. The system impairment due to PMD at a specific time and wavelength depends on the DGD at that time and wavelength. So, means of establishing useful limits on the DGD distribution, as it relates to the optical fibre cable PMD coefficient distribution and its limits, have been developed and are documented in IEC/TR 61282-3. The metrics of the limitations of the DGD distribution follow:

- Reference link length, L_{Ref}: A maximum link length to which the maximum DGD and probability will apply. For longer link lengths, multiply the maximum DGD by the square root of the ratio of actual length to the reference length.
- Typical maximum cable length, L_{Cab}: The maxima are assured when the typical individual cables of the concatenation or the lengths of the cables that are measured in determining the PMD coefficient distribution are less than this value.
- Maximum DGD, DGD_{max}: The DGD value that can be used when considering optical system design.
- Maximum probability, P_F: The probability that an actual DGD value exceeds DGD_{max}.

NOTE – The determination of the contribution of components other than optical fibre cable is beyond the scope of this Recommendation, but is discussed in IEC/TR 61282-3.

I.4 Non-linear coefficient

The effect of chromatic dispersion is interactive with the non-linear coefficient, n_2/A_{eff}, regarding system impairments induced by non-linear optical effects (see ITU-T Recs G.663 and G.650.2). Typical values vary with the implementation. The test methods for non-linear coefficient remain under study.

I.5 Tables of common typical values

The values in Tables I.1 and I.2 are representative of concatenated optical fibre links according to I.1 and I.3, respectively. The implied fibre induced maximum DGD values in Table I.2 are intended for guidance in regard to the requirements for other optical elements that may be in the link.

Table I.1/G.655 – Link attenuation values

Attenuation coefficient	Wavelength region	Typical link value
(Note)	1530-1565 nm	0.275 dB/km
	1565-1625 nm	0.35 dB/km
NOTE – Typical link value corresponds to the link attenuation coefficient used in ITU-T Recs G.957 and G.692.		

Table I.2/G.655 – Differential group delay

Maximum PMD_Q (ps/√km)	Link length (km)	Implied fibre induced maximum DGD (ps)	Channel bit rates
No specification			Up to 2.5 Gbit/s
0.5	400	25.0	10 Gbit/s
	40	19.0 (Note 1)	10 Gbit/s
	2	7.5	40 Gbit/s
0.20	3000	19.0	10 Gbit/s
	80	7.0	40 Gbit/s
0.10	> 4000	12.0	10 Gbit/s
	400	5.0	40 Gbit/s
NOTE 1 – This value applies also for 10 Gigabit Ethernet systems. NOTE 2 – Cable section length is 10 km except for the 0.10 ps/√km, > 4000 km link, where it is set to 25 km, the probability level is $6.5 \cdot 10^{-8}$.			

I.6 Examples of implementation

The following are examples of implementations that are designed to optimize various tradeoffs in power, channel spacing, amplifier separation, link length and bit rate. All these examples are primarily variations in the allowed chromatic dispersion, dispersion slope, and non-linear coefficient. These are examples only, which do not preclude other possible implementations. The example identifiers are arbitrary and do not reflect any priority.

Table I.3/G.655 – Examples for λ_{min} = 1530 nm and λ_{max} = 1565 nm

Example ID	D_{min} (ps/nm·km)	D_{max} (ps/nm·km)	Sign	Typical dispersion coefficient at 1550 nm (ps/nm·km)	Typical dispersion slope at 1550 nm (ps/nm^2·km)
A	1.3	5.8	+	3.7	0.070
B	2.0	6.0	+	4.2	0.085
C	2.6	6.0	+	4.4	0.045
D	5.0	10.0	+	8.0	0.058
E	1.0	6.0	–	–2.3	0.065
NOTE – Corresponding values of chromatic dispersion for the 1600 nm wavelength region are under consideration.					

I.7 Chromatic dispersion coefficient limits for Tables D and E

The equations bounding the chromatic dispersion coefficient vs wavelength are based on two surveys, one for the fibres represented by Table D and one for the fibres represented by Table E. There were five and four vendors respectively. Each provided average and standard deviation as a function of wavelength for wavelengths from 1460 to 1625 nm in 5 nm increments. For wavelength and vendor, the average plus and minus three standard deviation was calculated. Then the minimum and maximum across vendors was calculated. These results were fitted with a line spline using a breakpoint at 1550 nm to minimize the sum of absolute values of the difference while maintaining the principle of including all the data within the envelope.

The results for Tables D and E are shown in Figures I.1 and I.2 respectively. The solid lines are the limits from clause 7. The rest of the data represent the survey results.

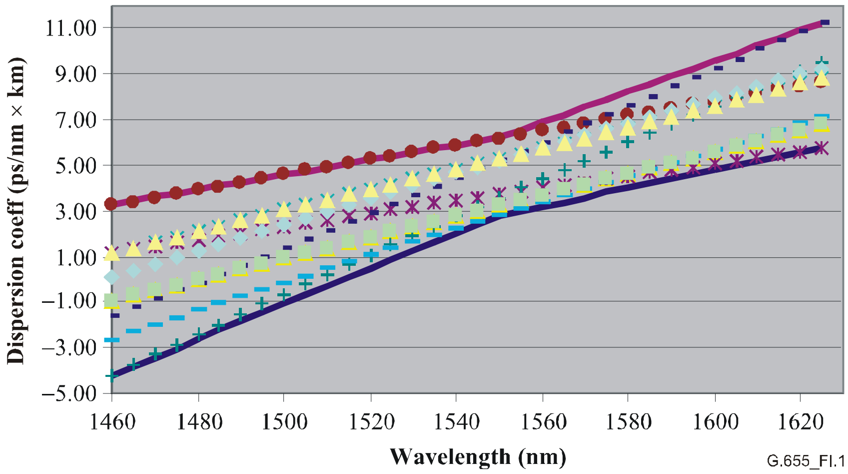

Figure I.1/G.655 – Table D fibre dispersion boundary

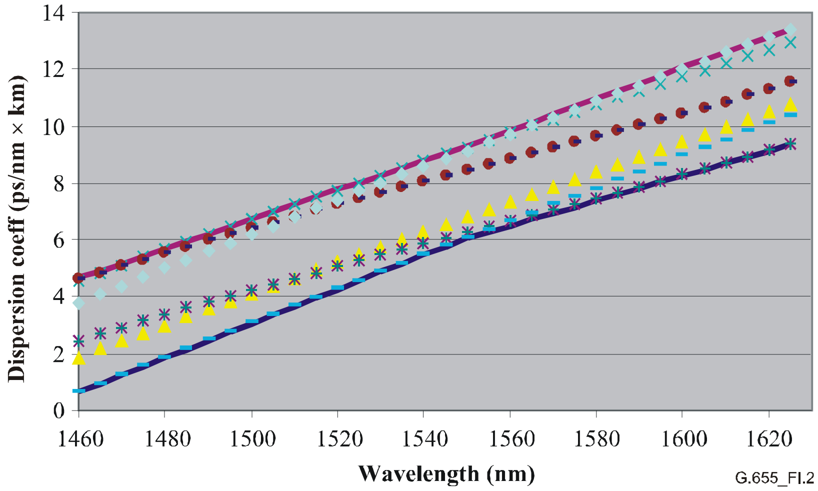

Figure I.2/G.655 – Table E fibre dispersion boundary

The limits in clause 7 are for individual fibres. The range of values associated with links which are a concatenation of individual fibres can be smaller. For G.652 fibres, where the diversity of values from vendor to vendor is reduced, the average plus one standard deviation, which is documented in Supplement 39 to ITU-T G-series Recommendations, can be used for system limit considerations.

The methodology described above was applied to determine the bounding curves that include all the average plus or minus one standard deviation results. The results are presented graphically in Figures I.3 and I.4. The plus or minus three standard deviation data are also presented for comparison. The equations that bound the plus or minus one standard deviation survey results are in Tables I.4 and I.5.

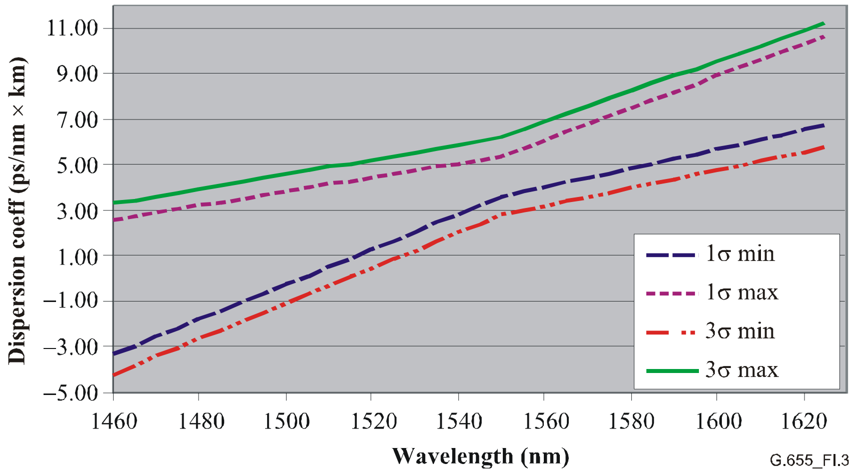

Figure I.3/G.655 – Comparison of Table D fibre dispersion boundaries

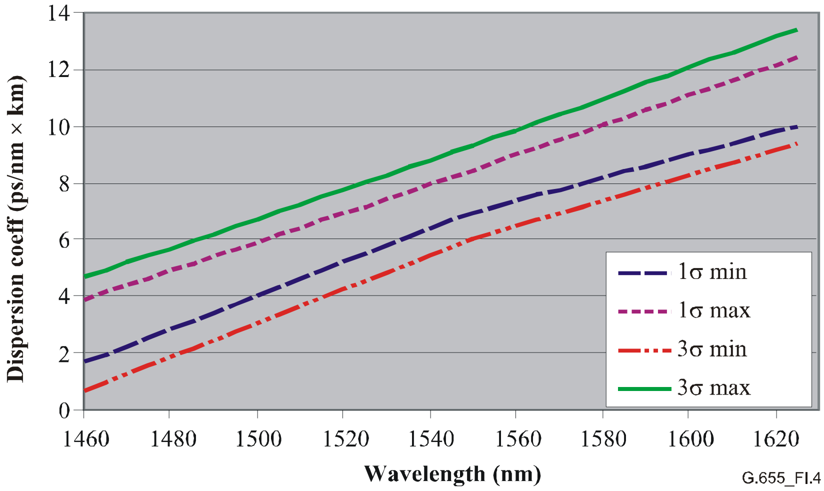

Figure I.4/G.655 – Comparison of Table E fibre dispersion boundaries

Table I.4/G.655 – Table D fibre ± one standard deviation limits

Chromatic dispersion coefficient (ps/nm·km)	$D_{min}(\lambda)$: 1460-1550 nm	$\frac{6.94}{90}(\lambda-1460)-3.34$
	$D_{min}(\lambda)$: 1550-1625 nm	$\frac{3.13}{75}(\lambda-1550)+3.60$
	$D_{max}(\lambda)$: 1460-1550 nm	$\frac{2.78}{90}(\lambda-1460)+2.60$
	$D_{max}(\lambda)$: 1550-1625 nm	$\frac{5.28}{75}(\lambda-1550)+5.38$

Table I.5/G.655 – Table E fibre ± one standard deviation limit

Chromatic dispersion coefficient (ps/nm·km)	$D_{min}(\lambda)$: 1460-1550 nm	$\frac{5.28}{90}(\lambda-1460)+1.68$
	$D_{min}(\lambda)$: 1550-1625 nm	$\frac{3.05}{75}(\lambda-1550)+6.96$
	$D_{max}(\lambda)$: 1460-1550 nm	$\frac{4.56}{90}(\lambda-1460)+3.89$
	$D_{max}(\lambda)$: 1550-1625 nm	$\frac{3.96}{75}(\lambda-1550)+8.45$

BIBLIOGRAPHY

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