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Fibre optic communication system design guides –

Part 3:
Calculation of link polarization mode dispersion

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 3: Calculation of link polarization mode dispersion

FOREWORD

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IEC 61282-3, which is a technical report, has been prepared by subcommittee 86C: Fibre optic systems and active devices, of IEC technical committee 86: Fibre optics.

This second edition cancels and replaces the first edition published in 2002. It is a technical revision that includes the following significant changes:

a) the title has been changed to better reflect its applicability to links;
b) Equations (1) and (2) were simplified in order to align with agreements in the ITU-T.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
86C/701/DTR	86C/720/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61282 series, published under the general title *Fibre optic communication system design guides,* can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

INTRODUCTION

Polarization mode dispersion (*PMD*) is usually described in terms of a differential group delay (*DGD*), which is the time difference between the principal states of polarization of an optical signal at a particular wavelength and time. *PMD* in cabled fibres and optical components causes an optical pulse to spread in the time domain, which may impair the performance of a fibre optic telecommunication system, as defined in IEC 61281-1.

FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 3: Calculation of link polarization mode dispersion

1 Scope

This part of IEC 61282 provides guidelines for the calculation of polarization mode dispersion (*PMD*) in fibre optic systems to accommodate the statistical variation of *PMD* and differential group delay (*DGD*) in optical fibre cables and components.

This technical report describes methods for calculating *PMD* due to optical fibre cables and optical components in an optical link. The calculations are compatible with those documented in the outdoor optical fibre cable specification IEC 60794-3. Example calculations are given to illustrate the methods for calculating total optical link *PMD* from typical cable and optical component data. The calculations include the statistics of concatenating individual optical fibre cables drawn from a specified distribution. The calculations assume that all components have *PMD* equal to the maximum specified value.

The calculations described cover first order *PMD* only. The following subject areas are currently beyond the scope of this technical report, but remain under study:

– calculation of second and higher order *PMD*;
– accommodation of components with polarization dependent loss (PDL) – if it is assumed that PDL is negligible in optical fibre cables;
– system impairments (power penalty) due to *PMD*;
– interaction with chromatic dispersion and other nonlinear effects.

Measurement of *PMD* is beyond the scope of this technical report. Methods of measurement of *PMD* of optical fibre and cable are given in IEC 60793-1-48. The measurement of optical amplifier *PMD* is in IEC 61290-11-1. The measurement of component *PMD* is in IEC 61300-3-32. Measurement of link *PMD* is given in 61280-4-4. A general theory and guidance on measurements is given in 61282-9.

2 Basic design models for total system *PMD* performance

2.1 Notation

For cabled fibre and components with randomly varying *DGD*, the *PMD* frequency domain measurement is based on averaging the individual *DGD* values for a range of wavelengths. The probability density function of *DGD* values is known to be Maxwell for fibre, and is assumed to be Maxwell, in effect, for components. The single parameter for the Maxwell distribution scales with the *PMD* value.

For long fibre and cable (typically longer than 500 m to 1 000 m), the *PMD* value is divided by the square root of the length to obtain the *PMD* coefficient. For components, the *PMD* value is reported without normalization. The following terms and meanings will be used to distinguish the various expressions:

– *DGD* value	The differential group delay at a time and wavelength (ps)
– *PMD* value	The wavelength average of *DGD* values (ps)
– *PMD* coefficient	The length normalised *PMD* (ps/sqrt(km))
– *DGD* coefficient	The length normalised *DGD* (ps/sqrt(km))

NOTE The term "*DGD* coefficient" is used only in some of the calculations. The physical square root length dependence of the *PMD* value does not apply to *DGD*.

Deterministic components are those for which the *DGD* may vary with wavelength, but not appreciably with time. The variation in wavelength may be complex, depending on the number and characteristics of the sub-components within. For these types of components, either the maximum *DGD* is reported or the wavelength average is reported as the *PMD* value. For components with multiple paths, such as an optical demultiplexer, the maximum *DGD* of the different paths should be reported as the *PMD* value.

2.2 Calculation of system *PMD*

PMD values of randomly varying elements can be added in quadrature. Annex A shows the basis of this, as well as one basis for concluding that the Maxwell distribution is appropriate to describe the distribution of *DGD* values. Annex A describes the concatenation in terms of the addition of rotated polarization dispersion vectors (pdv) which are, for randomly varying components, assumed to be random in magnitude and direction over both time and wavelength.

For deterministic components, the evolution of the pdv with wavelength may be quite complex, but for each wavelength, there is a value that does not vary appreciably with time. Analysis of the relationships in Annex A shows that deterministic components that are randomly aligned in combination with random elements behave like random components.

For randomly varying components such as fibre, the statistics of *DGD* variation imply that there is little wavelength dependence of the *PMD* value. This leads to an equivalence between *PMD* measurement methods such as Jones Matrix Eigenanalysis (JME) and interferometric methods (IT) where the wavelength ranges of the two are different. For deterministic elements, there can be distinct dependence of both the *DGD* and *PMD* on the wavelength range. Therefore for these elements, when doing calculations which combine both randomly varying and deterministic elements, the combined values are only representative of the wavelength overlap.

The relationships of Annex A also show an analysis for an assumption that the deterministic components are randomly aligned. For this assumption, the *DGD* values are time randomised across the wavelengths by the fibre. The random alignment of these components with respect to the other elements leads to the following conclusions for deterministic components.

– The quadrature addition of *PMD* values can be used to calculate the contribution to system *PMD*.

– The Maxwell distribution can conservatively be used to describe the variation in *DGD* across time and wavelength.

The following two subclauses provide equations to calculate: a) the maximum *PMD* value for the link, b) the maximum *DGD* value for the link. In both cases, the maximum is defined in terms of a probability level that takes into account the statistics of the concatenation of individual cables drawn from a specified distribution of optical fibre cable. For maximum *DGD*, these statistics are combined with the Maxwell statistics of *DGD* variation. Clause 3 provides methods of calculating the relevant statistics for the contribution of optical fibre cable, which are used in combination with the component values below.

2.2.1 Link maximum *PMD*

The total maximum *PMD* value of a fibre optic system including optical fibre cables and other optical components is given by the following:

$$PMD_{\text{tot}} = \left[L_{\text{link}} PMD_Q^2 + \sum_i PMD_{Ci}^2 \right]^{1/2} \quad (1)$$

where

PMD_{tot} is the total link PMD value (ps);

PMD_Q is the link design value of the concatenated optical fibre cable (ps/√km);

L_{link} is the link length (km);

PMD_{Ci} is the PMD value of the i^{th} optical component (ps);

The link design value, PMD_Q, (see 3.1) defines a maximum in terms of the probability, Q, for links with at least M individual cable sections.

NOTE The PMD_Q parameter is not related to the Q factor used in bit error ratio calculations.

For a link for which the individual cabling sections have been measured, the term $L_{link} PMD_Q^2$ can be replaced by $\sum_i PMD_i^2$, where PMD_i is the PMD value (ps) of the i^{th} section.

The validity of these equations has been demonstrated empirically for systems composed of concatenated optical fibre cables [2].

2.2.2 Calculation of system maximum *DGD*

The total maximum DGD value of a fibre optic system including optical fibre cable and other optical components is given by one of the following:

$$DGD_{max\ tot} = \left[DGD_{maxF}^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} \quad (2)$$

where

$DGD_{max\ tot}$ is the maximum link DGD (ps);

DGD_{maxF} is the maximum concatenated optical fibre cable DGD (ps) (see below);

S is the Maxwell adjustment factor (see below);

PMD_{Ci} is the PMD value of the i^{th} component (ps);

For a statistical specification of optical fibre cable, the maximum DGD is defined by a probability, P_F, and reference length (see 3.2). It is computed from the convolution of the distribution of the concatenated link PMD distribution and the Maxwell distribution of DGD values. For a link that has been measured, such as described below Equation (1), the term DGD_{maxF} is replaced by $\left[S^2 \sum_i PMD_i^2 \right]^{1/2}$.

The S parameter relates to the probability, P_C, that a random component DGD value exceeds $S \cdot PMD_C$, assuming the Maxwell distribution. Table 1 shows the relationship of S to probability when the PMD value is defined as the wavelength average.

Table 1 – Probability based on wavelength average

S	Probability
3,0	4,2E-05
3,1	2,0E-05
3,2	9,2E-06
3,3	4,1E-06
3,4	1,8E-06
3,5	7,7E-07
3,6	3,2E-07
3,7	1,3E-07
3,775	6,5E-08
3,8	5,1E-08
3,9	2,0E-08
4,0	7,4E-09
4,1	2,7E-09
4,2	9,6E-10
4,3	3,3E-10
4,4	1,1E-10
4,5	3,7E-11

Annex B shows that the probability that a system *DGD* value, DGD_{tot}, exceeds DGD_{maxtot} is bounded by the sum of the two probabilities as:

$$P\left(DGD_{\text{tot}} > DGD_{\text{maxtot}}\right) \le P_F + P_C \qquad (3)$$

NOTE The notation $P(\;)$ indicates a probability statement relative to the inequality within the parenthesis.

The above equations are applicable to all links with length less than the reference length. An adjustment for longer lengths is included in 3.2. Equation (2) is relevant for the assumption that deterministic components are randomly aligned. The multiplication of the deterministic *PMD* values with the *S* parameter treats these elements as though their *DGD* values are distributed as Maxwell – a conservative assumption that allows the quadrature addition.

Equation (3) illustrates that the total probability of exceeding some overall maximum can be bounded by an addition that does not depend on the relative magnitude of $DGD\text{max}_F$ and $S{\cdot}PMD_C$. Given an overall probability target, one approach is to allocate half the overall allowed probability to fibre and half to components. Annex C provides a worked example.

3 Calculation of cabled fibre *PMD*

3.1 General

PMD is a stochastic attribute that varies in magnitude randomly over time and wavelength. The variation in the *DGD* value is described by a Maxwell probability density function that can be characterised by a single parameter, the *PMD* value (see Equation (16) in 3.3.1). This parameter may be the average of the *DGD* values measured across a wavelength band, or it may be the r.m.s. value of these *DGD* values, depending on the definition chosen. For mode coupled fibre, the *PMD* coefficient is the *PMD* value divided by the square root of length.

In accordance with the outdoor Sectional Specification for outdoor optical fibre cable, IEC 60794-3, the PMD of cabled fibre should be specified/characterised on a statistical basis, not on an individual fibre basis. Two methods for this specification are proposed: Method 1 can be used to obtain PMD_Q, used in 2.2.1, and Method 2 can be used to obtain $DGD_{\max F}$ and P_F, used in 2.2.2.

In the ITU Recommendation G.652 (and others), Method 1 forms a normative requirement and Method 2 is used to determine functionality for system performance, which is specified in terms of DGD_{maxtot} in Recommendations such as G.691 or G.959.1.

Subclause 3.4 shows how specification values for each method can be selected so the two methods are nearly equivalent.

Method 1 relies on the fact that the mean PMD coefficient of an optical link is the root mean square (quadrature average) of the mean PMD coefficients of the cabled fibres comprising the link. Method 2 assumes the same relationship.

Let x_i and L_i be the PMD coefficient (ps/√km) and length, respectively, of a fibre in the i^{th} cable in a concatenated link of N cables. The PMD coefficient, x_N (ps/√km), of this link is:

$$x_N = \left[\frac{\sum_{i=1}^{N} L_i x_i^2}{\sum_{i=1}^{N} L_i}\right]^{1/2} = \left[\frac{1}{L_{\text{Link}}}\sum_{i=1}^{N} L_i x_i^2\right]^{1/2} \tag{4}$$

If it is assumed that all cable section lengths are less than some common value, L_{Cab}, and simultaneously reducing the number of assumed cable sections to $M = L_{\text{Link}}/L_{\text{Cab}}$, then, for a link comprised of equal-length cables, $L_i = L_{\text{cable}}$, Equation (4) becomes

$$x_N \le x_M = \left[\frac{L_{\text{Cab}}}{L_{\text{Link}}}\sum_{i=1}^{M} x_i^2\right]^{1/2} = \left[\frac{1}{M}\sum_{i=1}^{M} x_i^2\right]^{1/2} \tag{5}$$

The variation in the concatenated link PMD coefficient, x_M, will be less than the variation in the individual cable sections, x_i, because of the averaging of the concatenated fibres.

Method 1 should be used with Equation (1) of 2.2.1. In Method 1, the manufacturer supplies a maximum PMD link design value, PMD_{Q}, that serves as a statistical upper bound for the PMD coefficient of the concatenated fibres comprising an optical cable link. For this case, the upper bound for the PMD value of the concatenation of optical fibre cables, $PMD_{F\text{Tot}}$, in Equation (1) becomes:

$$PMD_{F\text{Tot}} = PMD_Q \sqrt{L_{\text{Link}}} \tag{6}$$

Unless otherwise specified in the cabled fibre detail specification, the PMD link design value shall be less than 0,5 ps/√km, and the probability that a PMD coefficient of a link comprised of at least 20 cables will exceed the link design value shall be less than 10^{-4}. The link design value shall be computed using a method agreed upon between the buyer and cable manufacturer (see 3.2 for examples).