RAPPORT TECHNIQUE

TECHNICAL REPORT

CEI
IEC
TR 61282-3

First edition
2002-08

Fibre optic communication system design guides –

Part 3: Calculation of polarization mode dispersion

Guides de conception des systèmes de communication à fibres optiques –

Partie 3:
Calcul de la dispersion en mode de polarisation

Numéro de référence
Reference number
CEI/IEC/TR 61282-3:2002

Publication numbering

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Commission Electrotechnique Internationale
International Electrotechnical Commission
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CODE PRIX
PRICE CODE **W**

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FIBRE OPTIC COMMUNICATION SYSTEM DESIGN GUIDES –

Part 3: Calculation of 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.

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

Enquiry draft	Report on voting
86C/296/DTR	86C/346/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.

Annexes A, B, C, D and E are for information only.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

This document, which is purely informative, is not to be regarded as an International Standard.

The committee has decided that the contents of this publication will remain unchanged until 2006 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- withdrawn;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 polarization mode dispersion

1 Scope

The purpose of this technical report is to provide 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 guideline describes methods for calculating PMD due to optical fibre cables and optical components in an optical link. 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.

NOTE The statistical specification of the distribution of the PMD of optical fibre cables is a current work item to amend IEC 60794-3, in SC86A/WG3 [2][1]. The agreements following the last ballot (86A/501/CD) are aligned with the methods given in this technical report.

The calculations described cover first order PMD only. This study of PMD continues to evolve, therefore the material in this technical report may be modified in the future. 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. Guidelines on the measurement of PMD of optical fibre and cable are given in IEC 61941. The measurement of optical amplifier PMD will be documented in IEC 61290-11-1[2]. The measurement of component PMD will be documented in IEC 61300-3-32[3].

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 for random components. The single parameter for the Maxwell distribution scales with the PMD value.

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[1] Figures in brackets refer to the bibliography.

[2] To be published

[3] To be published

For long fibre and cable (typically longer than 500 m to 1000 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 normalized PMD (ps/sqrt(km))
– DGD coefficient	The length normalized 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.

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 if all deterministic components are at the end of the system and all their pdvs are aligned, the total contribution to the link DGD at a particular wavelength is equal to the sum of the individual DGD values of each deterministic component. The worst case contribution across all wavelengths is therefore the sum of maximum DGD values.

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, the wavelength range must be specified. 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 a more realistic assumption: the deterministic components are embedded within the system and randomly aligned. For this assumption, the DGD values are time randomized across the wavelengths by the downstream fibre. Furthermore, the random alignment of these components with respect to the other elements leads to the following conclusions for embedded 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 system, b) the maximum DGD value for the system. 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 System maximum PMD

The total maximum PMD value of a fibre optic system including optical fibre cable and other optical components is given by one of the following, depending on the placement of deterministic components:

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

$$PMD_{\mathrm{tot}} = \left[L_{\mathrm{link}} PMD_Q^2 + \sum_i PMD_{Ci}^2 + \sum_j PMD_{Dj}^2 \right]^{1/2} + PMD_{D\mathrm{last}} \qquad \text{(1b)}$$

where

PMD_{tot}	is the total system 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} randomly varying optical component (ps);
PMD_{Dj}	is the PMD value of the j^{th} deterministic optical component;
$PMD_{D\mathrm{last}}$	is the PMD value of the last non-embedded deterministic component.

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.

The validity of these equations has been demonstrated empirically for systems composed of concatenated optical fibre cables [2]. Equation (1a) is relevant assuming that all deterministic components are at the end of the system. Equation (1b) is relevant assuming that most deterministic components are embedded.

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, depending on the placement of deterministic components:

$$DGD\max_{\mathrm{tot}} = \left[DGD\max_F^2 + S^2 \sum_i PMD_{Ci}^2 \right]^{1/2} + \sum_j DGD\max_{Dj} \qquad \text{(2a)}$$

$$DGD\max_{\mathrm{tot}} = \left[DGD\max_F^2 + S^2 \left(\sum_i PMD_{Ci}^2 + \sum_j PMD_{Dj}^2 \right) \right]^{1/2} + DGD\max_{D\mathrm{last}} \qquad \text{(2b)}$$

where

$DGD\text{max}_{\text{tot}}$	is the maximum system DGD (ps);
$DGD\text{max}_F$	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} random component (ps);
$DGD\text{max}_{Dj}$	is the maximum DGD of the j^{th} deterministic component (ps);
PMD_{Dj}	is the PMD value of the j^{th} embedded deterministic component (ps);
$DGD\text{max}_{D\text{last}}$	is the maximum DGD of the last non-embedded deterministic component (ps).

The maximum DGD for optical fibre cable (see 3.2) is defined by a probability, P_F, and reference length. It is computed from the convolution of the distribution of the concatenated link PMD distribution and the Maxwell distribution of DGD values.

For components, the S parameter relates to the probability, P_C, that a random component DGD value exceeds $S \cdot PMD_C$, assuming the Maxwell distribution. The following table 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 $DGD\text{max}_{tot}$ is bounded by the sum of the two probabilities as:

$$P\left(DGD_{\text{tot}} > DGD\,\text{max}_{\text{tot}}\right) \leq P_F + P_C \tag{3}$$

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 (2a) is relevant for the assumption that all deterministic components are aligned and at the end of the system. Equation (2b) is relevant for the assumption that almost all deterministic components are randomly aligned and embedded in the system. 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. Because the Maxwell approximation for deterministic elements is conservative, if equation (2a) yields a $DGD\text{max}_{\text{tot}}$ value less than equation (2b), then equation (2a) value should be used (see annex E and [10]).

NOTE 1 The assumption of quadrature addition of DGD values of cabled fibre and randomly varying optical components is subject to experimental verification.

NOTE 2 While it is possible to combine the statistical distributions of random components with cabled fibre, it would require access to information that may not be generally available to any single vendor or customer.

NOTE 3 The DGD specified for deterministic components is assumed to be the maximum across the relevant wavelength range and environmental conditions

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 for both equations (2a) and (2b).

3 Calculation of cabled fibre PMD

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 characterized by a single parameter, the PMD value (see equation (15) in 3.2.1). This parameter may be the average of the DGD values measured across a wavelength band, or it may be the rms 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 ballot 86A/501/CD, the PMD of cabled fibre should be specified/characterized 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 $DGD\text{max}_F$ and P_F, used in 2.2.2. The method and specification values chosen shall be agreed upon between the buyer and the cable manufacturer. Paragraph 3.3 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:

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

If one assumes 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