Understanding PMD Specifications in New Advanced Very High-Speed Networks

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1. INTRODUCTION

With the advent of new advanced modulation formats being used to transport 40 Gbit/s and 100 Gbit/s transmission rates, a number of publications on polarization mode dispersion (PMD) and differential group delay (DGD) specifications have been produced in the industry. And due to the extensive amount of material available, it is easy to become overwhelmed and even get lost with it all. For this reason, we feel that it has become crucial to clarify PMD at high transmission rates by specifically looking into the work that has been done by the IEEE 802.3, the ITU-T, especially Study Group 15, in order to place what has been said on the subject in its proper and valid context.

2. UNDERSTANDING PMD AS A STATISTICAL PHENOMENON AND ITS RELATED CABLE SPECIFICATIONS

In the ITU-T Recommendations G.650.2 and G.691 [1,2], the PMD phenomenon, which causes pulse spreading in digital systems, is defined as the DGD between the fractions of an optical signal light pulse that are transmitted in two orthogonal polarized modes called the "principal states of polarization" (PSPs), as shown in figure 1.

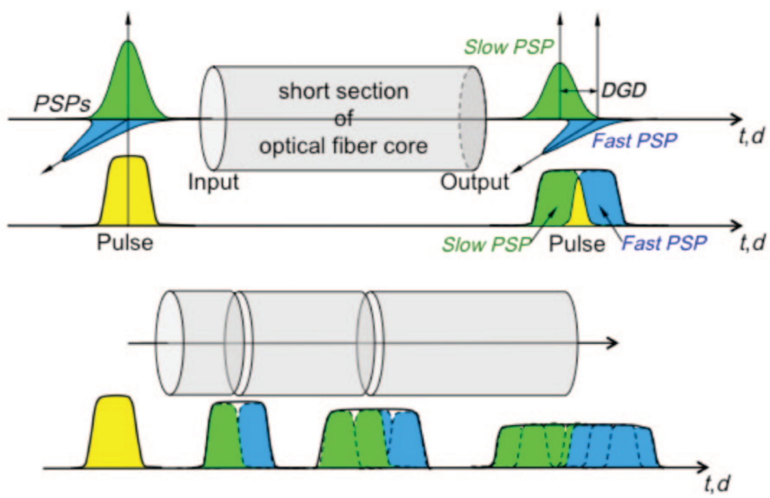


Figure 1. Example of pulse broadening from the DGD between the PSPs.

2.1 DGD_{Mean} versus DGD_{RMS}

The PMD value, typically in units of picoseconds (ps), is obtained from either of the following two approved ways:

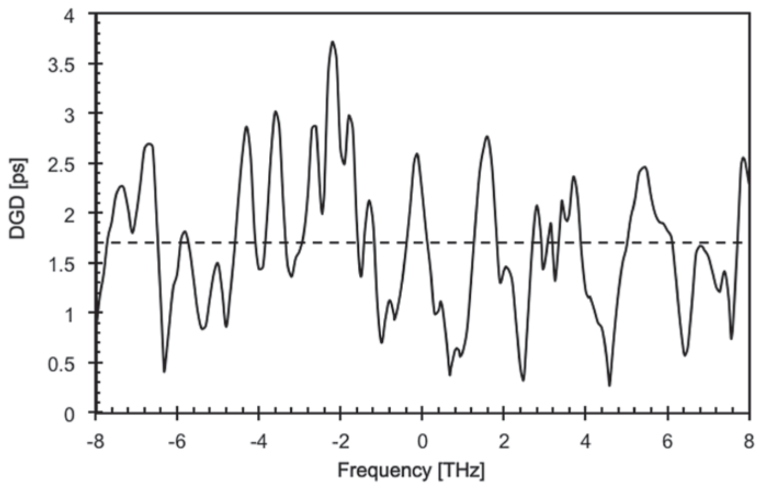
(a) DGD_{Mean}, defined as the linear average of the DGD values, is obtained over a wide frequency range or corresponding wavelength range;

(b) DGD_{RMS}, defined as the RMS average of the same DGD values, is obtained over the same frequency or wavelength range as the DGD_{Mean}.

It is important to note that frequency range or corresponding wavelength range must be as wide as possible, theoretically to the infinite. With a non-infinite range, the PMD value (DGD_{Mean}) suffers an uncertainty defined as follows [1]:

$$\text{PMD uncertainty [ps]} = \pm \frac{(2.3\ \text{PMD})^{1/2}}{4\pi\ (\text{frequency range})} \qquad (1)$$

If the cabled fiber is sufficiently long (in theory to infinite, practically to kilometers) and the corresponding PMD value is sufficiently high (in theory to the infinite, practically to ≥ 1 ps), the DGD values over frequency range or corresponding wavelength range will, ideally, be distributed randomly, as shown in figure 2 (i.e., random polarization mode coupling) and consequently, the probability density function (PDF) of this DGD distribution may be fit by a Maxwell equation[1].

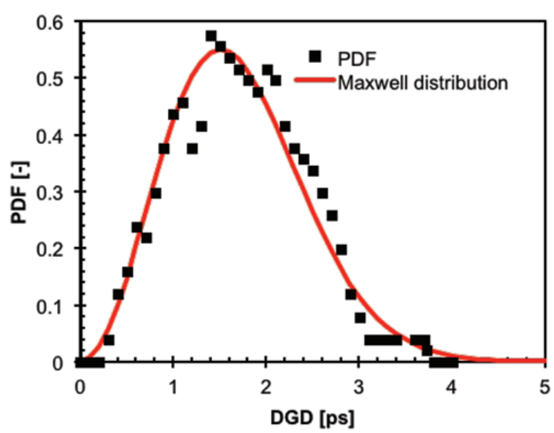


Note: DGD_{Mean} = 1.7 ps and DGD_{RMS} = 1.85 ps
Figure 2. DGD distribution over 16 THz (140.4 nm).

In this case, both the DGD_{Mean} and DGD_{RMS} are mathematically related to one another as follows [1,4]:

$$DGD_{Mean} = DGD_{RMS}\sqrt{\frac{8}{3\pi}} \qquad (2)$$

This simply means that the value of one can be obtained from the result of the other, but only if the DGD PDF is fit using the Maxwell curve, as seen in figure 3.



Note: The red line represents the Maxwell fit to the data
Figure 3. PDF (histogram) as a function of DGD data from figure 2.

[1] With lower PMD values, the fit becomes inapplicable and the PMD uncertainty is also calculated from equation (1) [3].

2.2 PMD_Q as a Cabled Fiber Specification

There exists a useful test that confirms the validity of the Maxwell equation fit to the DGD PDF: a one-to-one correspondence between the ideal Gaussian cross-correlation Fourier transform interferogram of the light coming out of the fiber and the ideal Maxwell equation fit to the corresponding DGD PDF. If the interferogram is not ideally Gaussian, the Maxwell equation cannot be used with confidence and fidelity to fit the DGD PDF. This means also that the relationship between the DGD_{Mean} and DGD_{RMS} is not straightforward in all cases, and measured values can vary greatly depending on the definition used by the test instrument and the complexity of the link design; figure 4 illustrates an example of such a validity test.

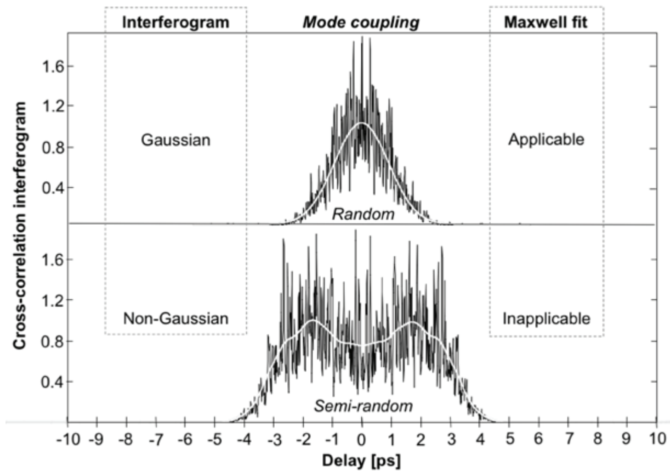


Figure 4. Interferograms in case of random (from figure 2) and semi-random mode couplings and applicability of Maxwell fit.

A PMD link design value, PMD_Q [5-10], is used as a PMD coefficient specification for cables/links. In that case, the PMD_Q (coefficient) serves as an upper bound for the PMD coefficient of a long optical cabled fiber within a defined link.

Fiber			PMD_Q (coefficient) [ps/km$^{1/2}$]
ITU-T		IEC	
Type	Category	60793-2-50	
G.652	A and C [1]	B1.1	≤ 0.5
	B and D [1]	B1.3	≤ 0.20
G.653	A	B2	≤ 0.5
	B		≤ 0.20 [2]
G.654	A	B1.2	≤ 0.5
	B and C		≤ 0.20
G.655	A and B	B4	≤ 0.5
	C, D and E		≤ 0.20
G.656	-	B5	≤ 0.20
G.657	A	B6	≤ 0.20
	B		TBD (Not essential)

[1] G.652.C and G.652.D fibers are also called low water-peak fibers
[2] Larger values can be agreed between manufacturer and user

Table 1. Recommended (standardized) values of cable maximum PMD coefficient [5-10].

In conclusion, the PMD_Q specification can only be used for cabled fibers in production, and installed links, spans and cable sections, with careful consideration for PMD measurement uncertainties, as discussed above.

2.3 DGD_{Max} as a System Specification

The maximum DGD, DGD_{Max}, is used as a PMD specification for system transmissions. DGD_{Max}, is defined as a DGD value corresponding to a PDF value taken as the probability that the transmission system will experience a DGD value larger than DGD_{Max} over a duration *t* as specified in table 2 [2,10] corresponding to that said probability.

Due to the statistical nature of PMD, a relationship between DGD_{Max} and DGD_{Mean} exists and can only be defined probabilistically, assuming a statistics based on the Maxwell equation (figure 3) and using a ratio S of DGD_{Max} to DGD_{Mean}, as shown in table 2.

$S = \frac{DGD_{Max}}{DGD_{Mean}}$	Probability of DGD > DGD_{Max}	*t* per year when DGD > DGD_{Max}
2.5	1.5×10^{-3}	13.1 h
3.0	4.2×10^{-5}	22 min
3.1	2.0×10^{-5}	10.5 min
3.2	9.2×10^{-6}	5 min
3.25	6.19×10^{-6}	3.2 min
3.3	4.1×10^{-6}	2.15 min
3.4	1.8×10^{-6}	56.6 s
3.5	7.7×10^{-7}	24 s
3.6	3.2×10^{-7}	10.1 s
3.7	1.3×10^{-7}	4.1 s
3.75	8.21×10^{-8}	2.6 s
3.775	6.5×10^{-8}	2.0 s
3.8	5.1×10^{-8}	1.6 s
3.9	2.0×10^{-8}	0.63 s
4.0	7.4×10^{-9}	0.23 s

Table 2. Ratio of maximum to mean DGD and corresponding probabilities [2,10].

From a system standpoint, the average value of the random dispersion penalties due to PMD is included in the allowed path penalty. In this respect, a transmitter/receiver combination is required to tolerate an actual DGD of 0.3 (or 30%) of the bit period B with a maximum sensitivity degradation or optical signal-to-noise ratio (OSNR) penalty of approximately 1 dB (with 50% of pulse energy in each PSP). This is for low-dispersion systems. For high-dispersion systems, the penalty increases to 2 dB. Of course, if the OSNR penalty is set lower than above, the system will perform better.

System DGD_{Max} specifications can be found in a number of ITU-T Recommendations [2,11-18] for various applications and bit rates. The following provides a summary of DGD_{Max} specifications for 1 dB penalty–except when otherwise mentioned.

3. PMD SPECIFICATIONS (DGD_{MAX}) FOR VARIOUS SYSTEM APPLICATIONS

3.1 SDH/SONET

As shown in table 3, DGD_{Max} is specified up to 40 Gbit/s for SDH/SONET applications.

NRZ applications		Bit rate	DGD_{Max}
STM-x	OC-x	[Gbit/s]	[ps]
4	12	0.622	480
8	24	1.244 (1.25)	240
16	48	2.488 (2.5)	120
64	192	9.953 (10)	30
256	768	39.813 (40)	7.5 [1]

[1] Some fiber categories in accordance with ITU-T Recommendations of G.652, G.653 and G.655 fibers have a PMD coefficient too high to guarantee this DGD.

Table 3. Maximum DGD specifications for SDH/SONET applications

3.2 OTN

Depending on system design, DGD_{Max} is specified up to 100 Gbit/s for OTN applications, as shown in table 4 and table 5.

OTN Applications	Bit rate [Gbit/s]	DGD_{Max} [ps] NRZ	RZ	Conditions
OTU1 + FEC	2.666	120	-	-
OTU2 + FEC	10.709	30	-	-
OTU3 + FEC	43.018	7.5 [1]	11.5	RZ33 (33% NRZ), 0.8xBR Rx BW, from simulation
			9.5	RZ50 (50% NRZ), 0.8xBR Rx BW, from simulation
			9.5	CS-RZ [19]

[1] Some fiber categories in accordance with ITU-T Recommendations G.652, G.653 and G.655 fibers have a PMD coefficient too high to guarantee this DGD

Table 4. Maximum DGD specifications for OTN applications [15-18].

OTN Application		OTL4.4 [1]	
Parameters	Units		
Center frequency / wavelength (operating wavelength range)	nm	231.4 THz / 1295.56 nm (1294.53 to 1296.59) 230.6 THz / 1300.05 nm (1299.02 to 1301.09) 229.8 THz / 1304.58 nm (1303.54 to 1305.63) 229.0 THz / 1309.14 nm (1308.09 to 1310.19)	
Channel spacing	GHz	800	
Number of channels	–	4	
Bit rate	Gbit/s	4 x 27.953 = 111.810	
Fiber type	–	G.652	
Reach	km	10 km for NRZ / 40 km for RZ	
Maximum attenuation	dB	6.3	18
DGD_{Max}	ps	10 (8 at 20% of bit period)	10.3 at ~26% of bit period

[1] OTL4.4 (OTU4 signal running on four channels also called “lanes”) = 255/227 x 24.883200 Gbit/s = 27.952493 Gbit/s per lane or 111.810 Gbit/s in total.

Table 5. Maximum DGD specifications for the OTN OTL4.4 application [18].

3.3 Ethernet

PMD is considered for Ethernet-based transport in IEEE 802.3 standardization working group. In Ethernet, PMD (DGD_{Max}) is specified up to 100 Gbit/s, as shown in table 6.

Ethernet Application		10GBASE-L	10GBASE–E	10GBASE-LX4	40GBASE-LR4	100G BASE–LR4	100G BASE–ER4
Parameter	Units						
Signaling rate	Gbit/s	9.95328 (**LW**) 10.3125 (**LR**)	9.95328 (**EW**) 10.3125 (**ER**)	4 x 3.125	4 x 10.3125 (41.25 Gbit/s)	4 x 25.78125 (103.125 Gbit/s)	
Channel spacing	-	-	-	CWDM (13.4 nm)	CWDM (20 nm)	DWDM (800 GHz)	
Wavelength range Center wavelength (wavelength range) Center frequency (wavelength range)	nm or THz	1260 to 1355	1530 to 1565	1269.0 to 1282.4 1293.5 to 1306.9 1318.0 to 1331.4 1342.5 to 1355.9	1271 nm (1264.5 to 1277.5) 1291 nm (1284.5 to 1297.5) 1310 nm (1304.5 to 1317.5) 1331 nm (1324.5 to 1337.5)	231.4 THz (1294.53 to 1296.59) 230.6 THz (1299.02 to 1301.09) 229.8 THz (1303.54 to 1305.63) 229.0 THz (1308.09 to 1310.19)	
Fiber type	–	G.652					
Reach	km	10	40 [1,2]	10	10	10	40 [1,2]
DGD_{Max}	ps	10	19 PDF = $1.3 \cdot 10^{-7}$	–	10	8	10.3

[1] Links longer than 30 km for the same link power budget are considered as being engineered links; attenuation for such links needs to be less than the worst case specified for B1.1, B1.3 or B6A single-mode fiber
[2] With DGD_{Max} / DGD_{Mean} = 3.75 (2.6 s/y), the link PMD coefficient is equal to 0.8 ps/√km

Table 6. Maximum DGD specifications for Ethernet applications [21, 22].

4. PMD SPECIFICATIONS (DGD_{Max}) FOR VERY HIGH BIT RATE ADVANCED MODULATION FORMAT SYSTEM APPLICATIONS

4.1. NRZ and RZ

Many proposals have been made over the years for PMD of very high-speed transmission systems using advanced modulation formats. Examples are provided in tables 7 to 10.

Modulation format		NRZ				50% RZ		
Parameters	**Units**	NRZ	OBD/PSBT	DPSK	DQPSK	DPSK	DQPSK	OPFDM-DQPSK
Bit rates	Gbit/s	43.018						
OSNR penalty	dB	1						
BER	–	10^{-4}						
DGD_{Max}	ps	8.3	6.2	8.7	16.8	9.7	20	30.7

Table 7. Maximum DGD for various modulation format applications [19].

4.2. OTN

Application		40G / OTU3+ FEC								
Parameters	**Units**									
Operating wavelength range	nm	1530-1565								
Fiber type	–	G.652 and G.655								
Modulation format	–	ODB/PSBT	NRZ-DPSK	NRZ-p-DPSK 66 GHz FSR	P-DPSK	RZ-QPSI	RZ-DQPSK (coherent)	OPFDM-RZ-DQPSK	RZ-AMI	DP-QPSK (coherent)
Bit rate	Gbit/s	43.018					2 x 21.509	2 x 21.509	43.018	4 x 10.7545
DGD_{Max} (1-dB OSNR penalty)	ps	5.5/7	8	7	6	9	18/20	20	9.5	75

Table 8. Maximum DGD for various modulation format applications [19].

Application		100G / OTU4 (1)									
Parameters	**Units**										
Operating wavelength range	nm	1530-1565 (presumed)									
Fiber type	–	G.652 and G.655 (presumed)									
Modulation format	–	NRZ		NRZ-DQPSK					ODB/PSBT		
Bit rate	Gbit/s	111.810 4 x 27.953	130 3 x 43.018	43.018	111.810 2 x 55.905	111.810 4 x 27.953	130 2 x 65	130 3 x 43.018	43.018	111.810 4 x 27.953	130 3 x 43.018
DGD_{Max} (1-dB OSNR penalty, BER = 1×10^{-4})	ps	2.9	2.5	16	5.8	6.1	5	5.3	7	2.7	2.3

Table 9. Maximum DGD for various modulation format applications [19].

Application		100G / OTU4 (2)										
Parameters	**Units**											
Operating wavelength range	nm	1530-1565 (presumed)										
Fiber type	–	G.652 and G.655 (presumed)					G.652 + DCF (80 km + 12.8 km)					
Modulation format	–	RZ-DQPSK			DP-QPSK		DPSK		DQPSK		DP-DQPSK	
Bit rate	Gbit/s	43.018	111.810 4 x 27.953	130 3 x 43.018	111.810 4 x 27.953	130 3 x 43.018	111.810 4 x 27.953	130 3 x 43.018	111.810 4 x 27.953	130 3 x 43.018	111.810 4 x 27.953	130 3 x 43.018
DGD_{Max} (1-dB OSNR penalty, BER = 1×10^{-4})	ps	19	7.3	6.3	27	23	9	7.7	18	15.4	36	30.8
							Ratio DGD to symbol duration = 10%					

Table 10. Maximum DGD for various modulation format applications [19].

4.3. Summary

As illustrated in figure 5, modulation formats, such as DQPSK (especially when used in a dual- or multiplexed-polarization schemes), offer the best potential for transmissions at very high speeds. For instance, at an eventual 400 Gbit/s, DGD_{Max} = 7 ps could be expected with RZ DP-QPSK.

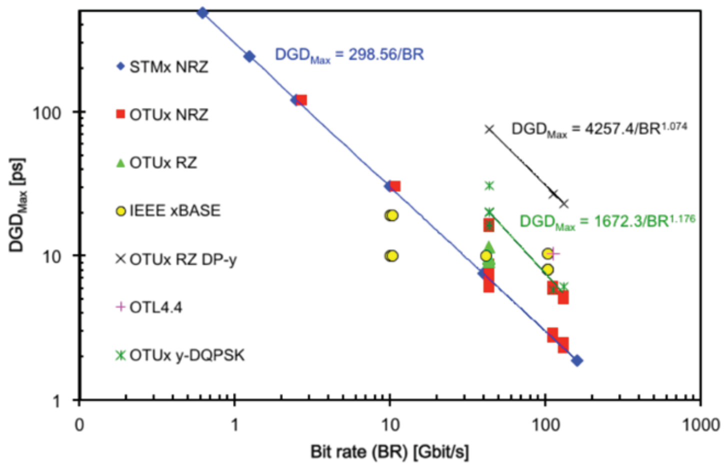


Figure 5. Summary of maximum DGD values for various lines codes, modulation formats as a function of bit rate.

5. CONCLUSIONS

In conclusion, only DGD_{Max} should be considered as a transmission system for PMD specification, while PMD_Q is for fibers in cables or links. Up to now, two PMD_Q specifications are available, 0.5 and 0.20 ps/√km and a number of DGD_{Max} specifications for SDH up to STM-256/OC-768, for OTN up to OTU4 and OTL4.4 (100 Gbit/s) and Ethernet (up to 100 Gbit/s).

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7. LIST OF ACRONYMS AND ABBREVIATIONS

AMI	Alternate-mark-inversion
BER	Bit error rate
BR	Bit rate
BW	Bandwidth
CS-RZ	Carrier-suppressed RZ
CWDM	Coarse wavelength division multiplexing
d	Distance
DGD	Differential group delay
DGD_{Mean}	Mean value of DGD distribution as a function of frequency or wavelength
DGD_{RMS}	RMS value of DGD distribution as a function of frequency or wavelength
DGD_{Max}	DGD value corresponding to a PDF value taken as the probability that the transmission system will experience a DGD value larger than DGD_{Max} over a duration *t*
DP-	Dual polarization
DPSK	Differential phase shift keying
DQPSK	Differential quadruple phase shift keying
DWDM	Dense wavelength division multiplexing
FEC	Forward error correction
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronic Engineers
ITU-T	International Telecommunication Union – Telecommunications standardization sector
M	Number of cable sections used to define PMD_Q
NRZ	Non-return to zero
OBD	Optical duo-binary
OC	Optical carrier
OPFDM	Orthogonal polarized frequency division multiplexing
OSNR	Optical signal-to-noise ratio
OTL	Optical channel transport lane
OTN	Optical transport network
OTU	Optical transport unit
PDF	Probability density function
P-DPSK	Partial DPSK
PMD	Polarization mode dispersion
PMD_Q	Statistical upper bound defined in terms of a probability level, Q, that a PMD coefficient value exceeds PMDQ of a long optical cabled fiber within a defined concatenated link of M cable sections
PSBT	Phase shaped binary transmission
PSP	Principal state of polarization
Q	Probability level that a concatenated PMD coefficient value exceeds PMDQ
RZ	Return to zero
S	Ratio of DGDMax to DGDMean
SDH	Synchronous digital hierarchy
SONET	Synchronous optical network
STM	Synchronous transport module
t	Time

8. ADDITIONAL USEFUL INFORMATION

SDH synchronous transfer mode level	SONET optical carrier level	Line rate [Gbit/s]	Typical name
STM-1	OC-3	0.15552	155 Mbit/s
STM-4	OC-12	0.62208	622 Mbit/s
STM-16	OC-48	2.48832	2.5 Gbit/s
STM-64	OC-192	9.95328	10 Gbit/s
STM-256	OC-768	39.81312	40 Gbit/s

OTN ODU line code [23]	Line rate [Gbit/s]
ODU0	1.244
ODU1	2.499
ODU2	10.037
ODU3	40.319
ODU4	104.795

OTN OTU line code [23]	Line rate [Gbit/s]
OTU1	2.666
OTU2	10.709
OTU3	43.018
OTU4	111.810

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