Milestone MJ1.2.3:
White Paper – PMD Emulation

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1 Introduction

Polarisation Mode Dispersion (PMD) can be an issue for many high bit rate transmission systems for backbone optical networks. Sometimes traditional On/Off Keying (OOK) Non-Return to Zero (NRZ) 10 Gbit/s systems and especially 40 Gbit/s systems with amplitude modulation schemes or even phase modulations without coherent detection and powerful digital signal processing are very sensitive to an uncompensated dispersion and therefore prone to stochastic behaviour of PMD. The stochastic behaviour limits the performance of transmission systems as transmission lines may have different PMD over time. The maximum tolerable PMD value by a transmission system is related to the system technology and, especially, bit rate. The value is generally recommended as one tenth of the bit interval duration. Tolerated PMD values for common modulation formats are listed in Table 1.1.

Modulation format	Symbol speed	Maximum tolerable PMD
OOK NRZ 40 Gbit/s	40 GBaud	2.5 ps
OOK NRZ 10 Gbit/s	10 GBaud	10 ps
OOK NRZ 2.5 Gbit/s	2.5 GBaud	40 ps
OOK NRZ 1 Gbit/s	1 GBaud	100 ps
ODB 40 Gbit/s	40 GBaud	3.5 ps
DPSK 40 Gbit/s	40 GBaud	3 ps
Coherent DP-QPSK 100Gbit/s	25 GBaud	30 ps

Table 1.1: Tolerable PMD for various transmission formats

Many network administrators therefore put considerable effort into detailed PMD measurements of their network links and provide collected values to network designers that estimate limits for deployment of transmission systems. Estimation is usually based on a comparison of the measured PMD value of network links against the PMD limit of transmission systems provided by vendors. The susceptibility of transmission systems may also be evaluated and verified by PMD emulators. The origin of PMD, its stability, emulator principle and measurements are described in more detail below.

2 Polarisation Mode Dispersion

The dispersion induced by PMD originates from the birefringence of optical fibres. Birefringence is a property of fibre material and the main sources of birefringence are non-perfect concentricity and the homogeneity of the optical fibre in the manufacturing design, as well as external stresses applied on the fibre cabling, such as bends or twist. Polarised light propagating through an optical fibre is split between two orthogonal Principal States of Polarisation (PSP), where each part is propagating by a slightly different speed. The time difference between light PSP at the end of an optical link is called Differential Group Delay (DGD). DGD varies over time and wavelength and usually follows Maxwellian distribution. PMD is close to the average value of Maxwellian distribution of DGD and can be estimated from the following equation:

$$PMD[ps] = \frac{maxDGD[ps]}{3.73}$$

where constant 3.73 comes from the definition of Maxwellian distribution.

The temporal variation of DGD creates the stochastic effect of dispersion. DGD is dependent on the refractive index of optical fibre and polarisation coupling between principal axes. Refractive index is a function of temperature and polarisation coupling is influenced by external stress. Therefore environmental variances in both weather and vibrations have a direct impact on the PMD value.

3 PMD Stability

Manufacturing processes can keep PMD in a range usually below 0.2 ps/√km. The deployment of optical cables induces additional stresses on the optical fibres inside the cable and thus changes the PMD value of fibres. Optical cables are generally deployed as hanged or grounded, with a distinct impact on their PMD value. Once an optical link is deployed, a PMD measurement for all fibres in the optical cable is necessary to characterise their PMD values and put limits on the allowed transmission for each optical fibre. Hanged aerial cables are more susceptible to weather and temperature change. Also, their PMD changes rapidly with wind, frost and day/night time. Grounded cables have a slower rate of change of their PMD value from weather and temperature, but react also to vibration caused, for example, by heavy moving vehicles. An example is an optical cable along a railway line that changes its PMD value as a train moves along it. Therefore successful measurement of PMD is done over several days or even weeks to estimate the worst-case PMD and limits for transmission systems.

4 PMD Emulator Principle

PMD emulators utilise various concepts to achieve stochastic behaviour of PMD. Essentially these devices emulate the Maxwellian distribution of DGD as a statistical set of DGD values that are set over a certain time period. A basic scheme that emulates DGD is a set of two polarisation beam splitters (PBSs) connected together with a variable delay line at one of their connection points, as displayed in Figure 4.1. A step motor with proper electronic control is used in this setup to change the delay line. Up-to-date PMD emulators utilise liquid crystals, highly birefringent polarisation-maintaining fibres or uniaxial birefringence crystals to emulate the desired DGD. Larger values of DGD usually require 6–9 active crystal sections to achieve good DGD granularity.

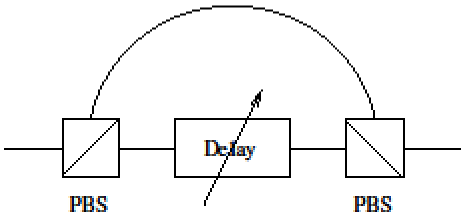

Figure 4.1: PMD emulator in principle

5 PMD Testing

Initial tests of 10 Gbit/s transmission were done with telecommunication testing equipment. A BERT tester with OOK NRZ 10 Gbit/s ER-Xenpak was connected to a Deterministic Polarisation Controller (DPC) that scanned all states of polarisation during measurements. The signal then went to a Polarisation Mode Dispersion Emulator (PMDE) that added PMD to the signal. The signal was then analysed by the BERT again. Figure 5.1 shows the setup for the 10 Gbit/s test.

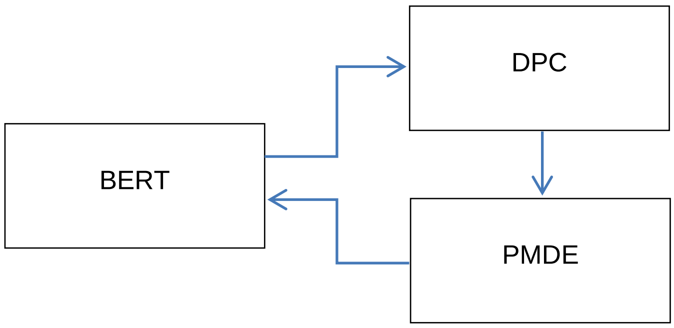

Figure 5.1: PMD test of OOK NRZ 10 Gbit/s

The statistical distribution of DGD values emulated by the PMD emulator is seen in Figure 5.2. Please note that the x axes in the figure show DGD three times bigger than the correct value; this is misleading and has been discussed with the PMDE vendor. Emulated DGD values are fitted by the red function of Maxwellian distribution. A BER of 10 GBit/s transmission in the presence of PMD can be seen in Figure 5.4 (top left).

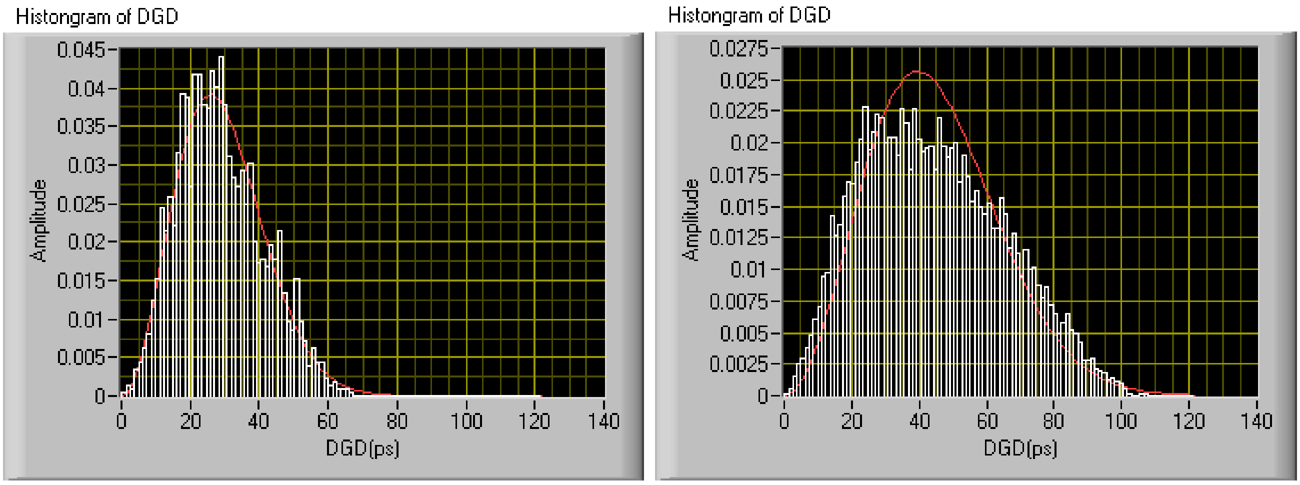

Figure 5.2: (left) DGD Histogram for PMD=10ps (right) DGD Histogram for PMD=16ps

Consecutive tests of more complex phase modulations were carried out using the StrataLight system. The StrataLight system works as a transponder with the BERT connected as a client, as shown in Figure 5.3.

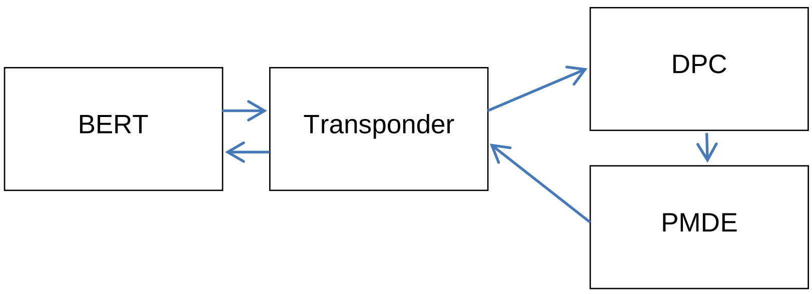

Figure 5.3: PMD test using StrataLight system as a transponder

The StrataLight system multiplexes incoming data sequences into a signal with phase modulation. The signal then travels to the DPC, the PMDE and through the StrataLight system back to the BERT. The lowest emulated PMD value of the PMD emulator was 3.5 ps, which is already greater than the expected tolerance of a 40 Gbit/s system. Therefore the measured operation with added PMD always showed errors. Figure 5.4 (top right) shows a BER of 10^{-5} before Forward Error Correction (FEC) and 10^{-7} after FEC for PMD 3.5 ps. Tests of 100 Gbit/s DP-QPSK have the opposite problem that resilience of this state-of-the-art modulation format for backbone networks is close to the maximum performance of PMDE. Therefore only a limited number of measurement points could be taken. Moreover, most of the impairments induced by PMD were corrected by FEC and only when a BER limit of 10^{-4} was reached was an increased error rate in the data observed. Figure 5.4 (bottom) displays that BER increased to 10^{-8} when PMDE inserted 27.5 ps of PMD and shows good PMD resiliency of the DP-QPSK modulation.

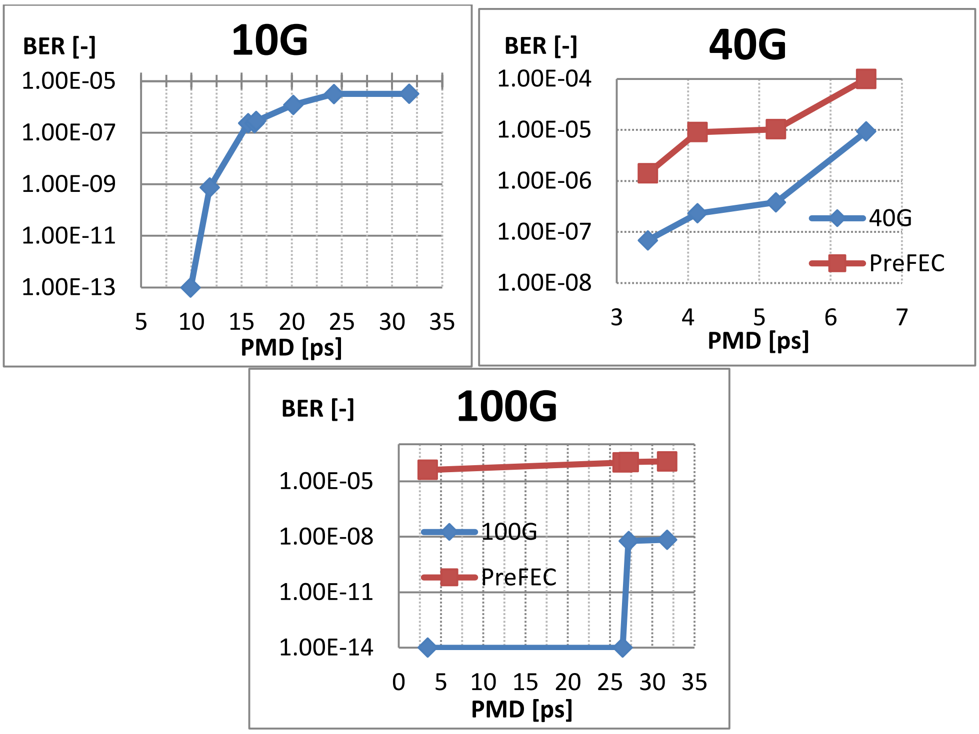

Figure 5.4: BER of telco modulations in presence of PMD: 10G (top left), 40G (top right) and 100G (bottom)

We have performed tests with transceivers of bit rates 10 Gbit/s, 40 Gbit/s and 100 Gbit/s. The 10 Gbit/s transceivers were ER Xenpaks with NRZ OOK modulation. The 40 Gbit/s and 100 Gbit/s transceivers were StrataLight systems from OPNext (now Oclaro) with DPSK and DP-QPSK modulations. Their expected resilience to PMD and test results are shown in Table 5.1.

ID	Modulation	Bit rate	PMD tolerance	PMD tolerance measured
ER-Xenpack	NRZ OOK	10 Gbit/s	10	10
StrataLight – Oclaro	DPSK	40 Gbit/s	3	Out of range
StrataLight – Oclaro	coherent DP-QPSK	100 Gbit/s	30	27.5

Table 5.1: Results of PMD emulation tests at available telecommunication modulations

6 Conclusion

We set up schemes to test the PMD resiliency of telecommunication systems and verified the resiliency of three different optical modulations. Although DPSK modulation was slightly out of range for our equipment, the other systems showed resiliency close to the expected values. The PMD emulation equipment has some software issues that have been discussed with its vendor. Although PMD is definitely troublesome, network impairment will likely affect mainly high bit rate, but low performance, modulation formats or traffic in metropolitan networks that usually exhibits more stress-induced PMD from the city environment. The new state-of-the-art modulation format of DP-QPSK supported by DSP has a large tolerance to network impairments and does not consider PMD as a critical network parameter.

Glossary

AM	Amplitude Modulation
BERT	Bit Error Rate Tester
DPC	Deterministic Polarisation Controller
DGD	Differential Group Delay
DP-QPSK	Dual Polarisation Quadrature Phase Shift Keying
DPSK	Differential Phase Shift Keying
DSP	Digital Signal Processing
NRZ	Non-Return to Zero
OOK	On/Off Keying
ODB	Optical Duo Binary
PBS	Polarisation Beam Splitter
PMD	Polarisation Mode Dispersion
PMDE	Polarisation Mode Dispersion Emulator
PM	Phase Modulation
PSP	Principal States of Polarisation