Variation of PMD-induced Outage Rates and Durations with Link Length on Buried Standard Single-mode Fibers

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Abstract: From first-order polarization-mode dispersion (PMD) outage analysis using measured differential group delay (DGD) data on buried standard single-mode fibers, we observed that the outage rates increase monotonically with link length, although not linearly.

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Introduction

Polarization-mode dispersion (PMD) may be a major impediment for network operators seeking to increase the per channel data rate on long-haul fiber-optic links. A marked improvement in the PMD tolerance of 10 Gb/s long-reach receivers will likely satisfy most length demands, obviating the need for PMD mitigation at 10 Gb/s. However, transmission speeds of 40 Gb/s and beyond will most likely require some form of PMD mitigation in long-haul applications. To ensure signal quality on their fiber at such higher rates, network engineers must anticipate the impact of PMD on various fiber routes. A solid understanding of PMD-induced system outages will help engineers and researchers to develop new and cost-efficient mitigation alternatives to maintain high network reliability.

The availability of PMD data measured over long time periods on installed, buried fibers is limited. In this paper we present measured differential group delay (DGD) data for different buried, standard single-mode fibers from which first-order PMD-induced outage rates and durations are estimated to improve our understanding of the variability of PMD.

Experimental setup

Experiments were conducted to measure the instantaneous DGD on different combinations of three 95-km fiber spans (1, 2, and 3) within a slotted-core, direct-buried, standard single-mode fiber-optic cable made available by Sprint. The combinations of fibers used are three individual fibers (1, 2, 3, each ~95 km), three 2-fiber concatenations (1-2, 2-3, 1-3, each ~190 km) and one 3-fiber concatenation (1-2-3, ~285 km). A polarization analyzer employing the Jones-Matrix-Eigenanalysis (JME) method was used. EDFAs were used along the fibers for 2- and 3-fiber concatenated measurements. On individual fibers, measurements were made at wavelengths from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm and were repeated every 3 hours on fiber 1 and every 1½ hours on fibers 2 and 3. For all the concatenated fiber combinations measurements were made at wavelengths from 1535 nm to 1565 nm with a spectral resolution of 0.1 nm and were repeated every 23 minutes.

Measurements were carried out for 86 days on fiber 1 (Nov. 9, 2001 - Feb. 2, 2002), 14 days on fiber 2 (May 4, 2002 - May 18, 2002), 64 days on fiber 3 (May 29, 2002 - Aug. 1, 2002), 18 days on 1-2 concatenation (Aug. 22, 2002 - Sept. 9, 2002), for 21 days on 2-3 concatenation (Aug. 1, 2002 - Aug. 22, 2002), for 16 days on 1-3 concatenation (Sept. 27, 2002 - Oct. 13, 2002) and for 34 days on 1-2-3 concatenation (April 13, 2004 - May 17, 2004). Over the 34 days 2,127 measurements were made on 1-2-3 concatenation across 300 discrete wavelengths representing 638,100 measured DGD values. The corresponding number of measured DGD values for individual fibers are 796492 for fiber 1, 271400 for fiber 2, 1232800 for fiber 3 and for 2-fiber concatenations are 339,000 for 1-2, 394,200 for 2-3, and 306,000 for 1-3.

Plots of DGD vs. wavelength and time

Using the measured data, plots of DGD as a function of wavelength and time were obtained and figures 1, 2 and 3 show in a color-coded format normalized DGD data (i.e., DGD/mean DGD) measured on one individual fiber (fiber 1), one 2-fiber concatenation (1-2) and the 3-fiber concatenation (1-2-3). From the plots it is evident that the DGD varies significantly with wavelength, relatively high-DGD events are spectrally localized, and that the variation of DGD with time is more rapid on concatenated fibers than on individual fibers.

A histogram of the measured, normalized DGD data on 1-2-3 fiber concatenation, shown in figure 4, is seen to have shape consistent with a Maxwellian distribution as expected. A curve representing a Maxwellian distribution for a 1-ps mean DGD is also plotted for comparison. Also, we observed that the histograms of measured DGD data on the other combinations of the three fibers were in good agreement with the Maxwellian pdf (plots not shown).

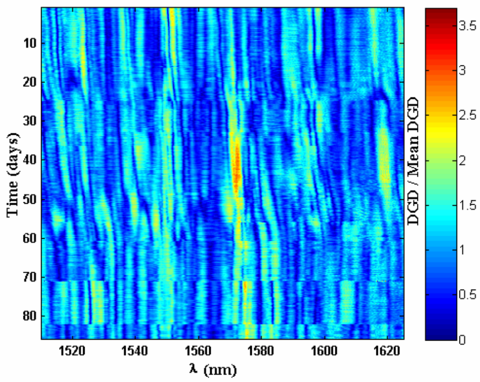

Fig. 1. Measured, normalized DGD vs. wavelength and time for fiber 1 (86 days of data).

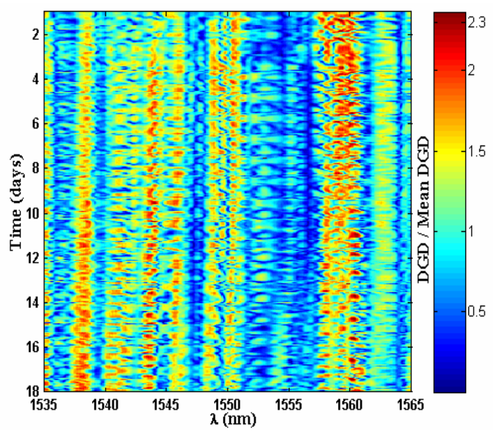

Fig. 2. Measured, normalized DGD vs. wavelength and time for 1-2 fiber concatenation (18 days of data).

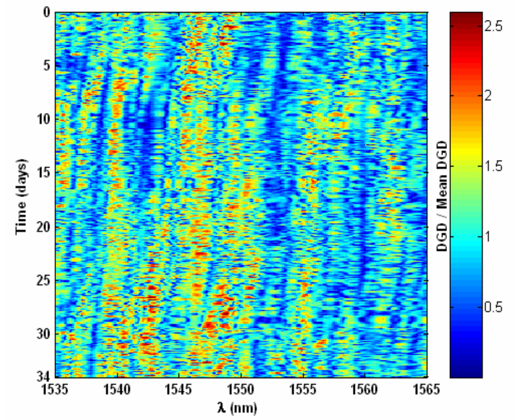

Fig. 3. Measured, normalized DGD vs. wavelength and time for 1-2-3 fiber concatenation (34 days of data).

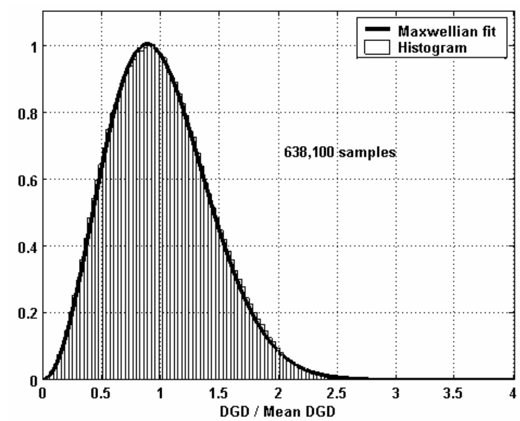

Fig. 4. Histogram of measured, normalized DGD data for 1-2-3 fiber concatenation (34 days of data).

First-order PMD outage rates and durations

A first-order PMD-induced outage is one which the instantaneous differential-group delay (DGD or $\Delta\tau$) exceeds a given threshold value, $\Delta\tau_{th}$. While the outage probability P_{out}, expressed in minutes/year, can be calculated using,

$$P_{out} = P(\Delta\tau \geq \Delta\tau_{th}) = 1 - \int_0^{\Delta\tau_{th}} f_\tau(\Delta\tau)\, d\Delta\tau \quad (1)$$

where $f_\tau(\cdot)$ is the Maxwellian probability distribution function (pdf) of DGD, P_{out} represents only the annualized outage probability and reveals nothing regarding outage rate or duration. Accurate estimation of the impact of PMD on network availability requires statistical analysis of DGD temporal variability. Caponi et al. [1] showed how the mean time between PMD-related outages for a given link could be estimated from its DGD temporal variations and the Maxwellian probability density function. They showed that the mean outage rate, R_{out} (defined as the mean number of outage events per unit time with units of events/year), is found using [1]

$$R_{out} = \frac{1}{2} f_\tau(\Delta\tau_{th}) \int_{-\infty}^{\infty} f_{\tau'}(\Delta\tau')\left|\Delta\tau'\right| d\Delta\tau' \quad (2)$$

where $\Delta\tau'$ is the time derivative of DGD, and $f_{\tau'}(\cdot)$ is the pdf of $\Delta\tau'$. While P_{out} is the same for all random variables with a Maxwellian pdf, it has been reported that R_{out} is not the same since differences in cable and installation affect the DGD temporal characteristics [1, 2]. The mean duration of DGD-induced outages can be determined using statistical analysis as well. Caponi et al. [1] showed that the mean outage duration, T_{out}, is

$$T_{out} = P_{out} / R_{out} \quad (3)$$

which has units of minutes.

Figure 5 shows the calculated outage probability, P_{out}, and the mean outage rate, R_{out}, for a given system threshold relative to the mean DGD on the three individual fibers. Figure 6 shows the mean outage, R_{out}, for a given system threshold relative to the mean DGD on the concatenated fibers.

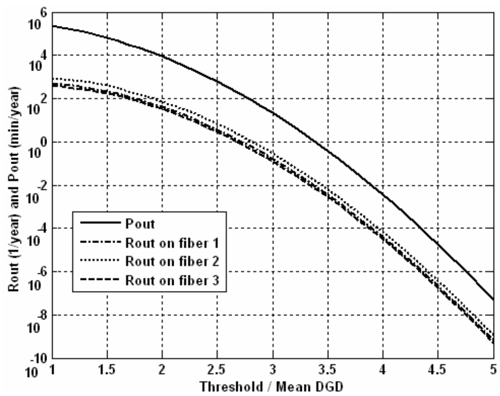

Fig. 5. Calculated outage probability, P_{out}, and mean outage rate, R_{out}, versus Threshold/Mean DGD for individual fibers.

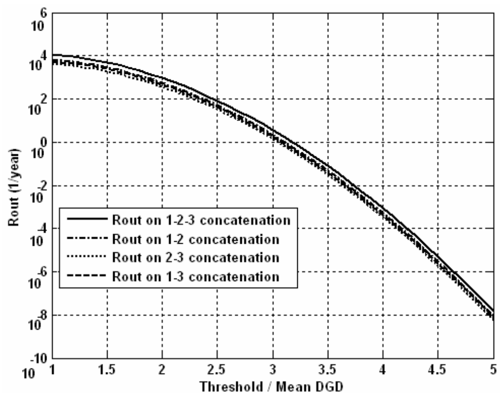

Fig. 6. Calculated mean outage rate, R_{out}, versus Threshold/Mean DGD for concatenated fibers.

Table 1. Predicted mean time between outages (MTBOs) and mean outage durations for different DGD tolerances

Length	Fiber	3*<DGD>	3.7*<DGD>
95 km	**Fiber 1** MTBO Outage duration	 6.39 years 136 min	 1648 years 108 min
95 km	**Fiber 2** MTBO Outage duration	 3.25 years 69 min	 833 years 55 min
95 km	**Fiber 3** MTBO Outage duration	 7.9 years 84 min	 2038 years 66 min
190 km	**1- 2** MTBO Outage duration	 0.46 years 9 min	 118 years 7 min
190 km	**2-3** MTBO Outage duration	 0.7 years 14 min	 180 years 11 min
190 km	**1-3** MTBO Outage duration	 0.55 years 11 min	 140 years 9 min
285 km	**1-2-3** MTBO Outage duration	 0.27 years 6 min	 71 years 4.6 min

From the above analysis, we can estimate the mean time between outages (MTBOs) (MTBO = $1/R_{out}$) and mean outage durations (using (3)) for various DGD tolerances for these fiber combinations. Table 1 lists these values for system thresholds of 3 and 3.7 times the mean DGD. From figures 5, 6 and the values in table 1, it can be observed that the first-order PMD outage rates (MTBOs) increased (decreased) by an order of magnitude for concatenated fibers (longer lengths) compared to individual fibers (shorter lengths). But the increase (decrease) in the outage rates (MTBOs) from the 2-fiber concatenations to the 3-fiber concatenation is less significant. This appears to indicate that the outage rates (MTBOs) are not increasing linearly as the fiber length is increased. We believe this observation is very useful for network engineers in predicting the first-order PMD outage rates on long-haul optical fiber links.

Conclusions

We have measured DGD over long time periods on different combinations of three 95-km fibers within a slotted-core, direct-buried, standard single-mode fiber-optic cable. From these measurements we observed that DGD varies slowly over time but rapidly over wavelength or frequency. We also observed that the temporal variation becomes more rapid for longer length fibers. From the first-order PMD outage analysis, we observed that the outage rates increase with length. However, these outage rates don't seem to increase linearly with the fiber length. This observation is significant for network operators who must assess the impact of PMD on network reliability.

References

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2. C. Allen, P.K. Kondamuri, D.L. Richards, and D.C. Hague, "Analysis and comparison of measured DGD data on buried single-mode fibers", *SOFM*, Boulder, CO, 195-198, Sept. 2002