Measured temporal and spectral PMD characteristics and their implications for network-level mitigation approaches

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Abstract– **Signal degradation due to polarization-mode dispersion (PMD) effects may become significant for signaling rates of 10 Gb/s, 40 Gb/s, and beyond. As expected, statistical analysis of variations in differential group delay (DGD) indicate that excursions from the mean DGD by factors of 3.7 or higher have very low probability. Temporal and spectral measurements of DGD were made on 95 km of buried standard SMF over an 86 day period to determine the distribution and rate of change of high DGD events. A drift time of about 3.4 days was found. The DGD data agree well with results of similar experiments reported in the literature. Coupling the drift time characteristic with the statistical behavior of DGD, we conclude that high-DGD episodes will be exceedingly rare and short lived. The impact of PMD on network operators is explored. Approaches are reviewed for network operators tasked with transporting high bit-rate channels over fiber links with known PMD characteristics.**

INTRODUCTION

In the phenomenon called polarization-mode dispersion (PMD), birefringence in the optical fiber provides two polarization-dependent group velocities for optical signals. In the high-coherence model of PMD (which assumes the coherence time of the light source is greater than the PMD-induced delays and no polarization-dependent loss) an input pulse will result in two orthogonally polarized pulses that preserve the shape of the original input pulse. The relative amplitudes of these two pulses is determined by the state of polarization (SOP) of the input pulse relative to the fiber's input principal states of polarization (PSPs). Thus for each pulse input, two pulses arrive at the receiver with different arrival times, called the differential group delay (DGD), $\Delta\tau$. This first-order model is frequency independent and is only valid over limited bandwidths. For wider bandwidths higher order effects must be considered resulting in frequency dependent polarization and dispersion [1], [2]. The bandwidth over which the PSPs can be assumed constant depend on the properties of the fiber and has been shown to vary inversely with the mean DGD, $\langle\Delta\tau\rangle$ [3]. While the minimum bandwidth of the PSPs in single-mode fibers was found to be always over 50 GHz [3], this bandwidth for standard single-mode fiber is of the order of 100 GHz [1].

PMD may become a major impediment for network operators seeking to increase the per channel data rate on long-haul fiber-optic links. While the DGD in buried fiber had negligible impact at 2.5-Gb/s signaling rates, upgrades to 10 Gb/s, 40 Gb/s and beyond will require increasingly more attention. While there are PMD challenges facing carriers at 10 Gb/s, these challenges are not as severe as originally feared. Major carriers are successfully deploying 10 Gb/s dense-wavelength division multiplexed (DWDM) links across the core of their networks. A marked improvement in the DGD tolerance of 10 Gb/s long-reach receivers (to about 40 ps) will likely satisfy most length demands, obviating the need for PMD compensation (PMDC). Signaling rates of 40 Gb/s and beyond will most likely require some form of mitigation in long-haul applications, such as robust modulation schemes or PMDC.

To ensure signal quality on their fiber at higher bit rates, network engineers must anticipate the impact of PMD on the various fiber routes. Design of a reliable network requires a good model of the PMD characteristics on each link. An understanding of the variability of both the DGD and the PSPs is required to specify appropriate transmission parameters. Factors such as the mean DGD, PMD correlation time and bandwidth, as well as second-order effects together with performance prediction models can provide this understanding.

While PMD is a vector quantity, with a magnitude (DGD) and a direction (PSP), we are deliberately focusing exclusively on DGD as this is a readily measured parameter on installed optical networks. The statistical distribution and behavior of PSPs has been extensively studied and reported elsewhere.

PMD STATISTICS

Mean DGD

For long optical fibers, the PMD figure of merit typically specified is its mean DGD, $\langle\Delta\tau\rangle$, (having units of ps) or its PMD coefficient, $\langle\Delta\tau\rangle/\sqrt{L}$, (having units of ps/$\sqrt{\text{km}}$) where L is the fiber length. The PMD for an installed (buried) fiber-optic cable is dominated by the inherent PMD of the bare fiber; however, the level of relaxation provided by the cabling and installation techniques also affect PMD. While the PMD in bare fiber is determined largely by the core-cladding concentricity achieved during manufacture, we have found that loose-tube cabling results in a lower PMD than other cabling methods, such as slotted core cabling. In addition, mechanical stresses introduced during cable installation (burial) also contribute to the PMD and will be affected by the installation practices used and whether the cable is in a protective conduit.

The mean DGD for a given fiber is a constant that represents both the average of DGD values at one time across a broad spectral bandwidth

$$\langle \Delta\tau \rangle = \frac{1}{N_\lambda} \sum_{i=1}^{N_\lambda} \Delta\tau(\lambda_i, t) \quad (1)$$

and the average of DGD values for a single wavelength over a long time period

$$\langle \Delta\tau \rangle = \frac{1}{N_t} \sum_{i=1}^{N_t} \Delta\tau(\lambda, t_i) \quad (2)$$

where $\Delta\tau(\lambda, t)$ is the DGD value at wavelength λ and time t. Although the mean DGD for an installed fiber is constant, changing environmental factors (e.g., temperature) cause the instantaneous DGD at a given wavelength, $\Delta\tau(\lambda, t)$, to vary randomly about that mean.

When various fiber segments are concatenated to form a single long fiber, the mean DGD of the overall fiber is found by

$$\langle \Delta\tau_{total} \rangle = \sqrt{\sum_i^N \langle \Delta\tau_i^2 \rangle} \quad (3)$$

where N is the number of segments.

Maxwellian distribution

The DGD for a given wavelength at any moment in time, $\Delta\tau(\lambda, t)$, is a random variable with a Maxwellian probability density function [4,5]

$$p(\Delta\tau) = \sqrt{\frac{2}{\pi}} \frac{\Delta\tau^2}{\sigma^3} e^{\left(\frac{-\Delta\tau^2}{2\sigma^2}\right)} \quad (4)$$

for $0 < \Delta\tau < +\infty$, where

$$\langle \Delta\tau \rangle = \sigma\sqrt{8/\pi} \quad (5)$$

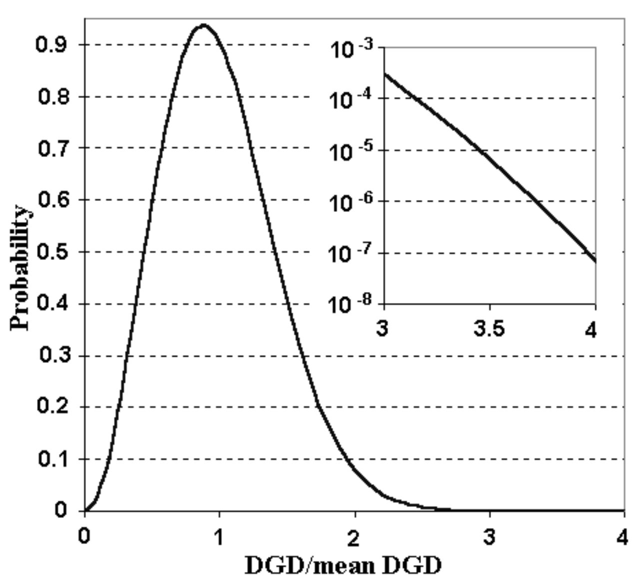

Figure 1. Maxwellian probability density function.

Therefore the single parameter $\langle\Delta\tau\rangle$ fully specifies the distribution. Figure 1 shows the Maxwellian probability density function normalized by the mean DGD.

Using this distribution, the probability of $\Delta\tau$ exceeding a particular value can be found using

$$P(\Delta\tau \geq X) = 1 - \int_0^X p(\Delta\tau) d\,\Delta\tau \quad (6)$$

For example, the probability of $\Delta\tau/\langle\Delta\tau\rangle$ exceeding 3.7 is 1.3×10^{-7}. Expressed another way, if the mean DGD of a fiber link is 10 ps, 99.99999% of the time the DGD will be less than 37 ps.

NETWORK DESIGN CONSIDERATIONS

In the design of a robust, long-haul fiber-optic network, the relationship between the maximum achievable link length and bit rate must be considered. For link designs where the maximum tolerable DGD is exceeded, techniques for coping with the effects of PMD must be explored.

Receiver DGD tolerance

The maximum link DGD that a receiver can tolerate before the signal degradation becomes unacceptable depends on a variety of factors, including modulation format, optical signal-to-noise ratio, and receiver design. For intensity-modulated, direct-detected (IM-DD) systems, Iannone et al. [6] found that when the transmitted signal excites both PSPs equally (a worst case condition), a 1-dB receiver sensitivity penalty results when the instantaneous DGD is about 23% of the signaling time period, T_{bit}. For a 2.5-Gb/s NRZ signal (T_{bit} is 400 ps), this corresponds to a tolerable DGD value of about 92 ps; at 10-Gb/s, about 23 ps is tolerable; and for a 40-Gb/s NRZ signal, this corresponds to about 5.7 ps. This maximum tolerable DGD level is representative of the NRZ IM-DD case; receiver DGD tolerance can be improved through careful receiver design, use of PMD-tolerant signaling formats, and the use of forward-correction codes (FEC). Khosravani and Willner [7] showed that RZ, chirped RZ, and dispersion-managed soliton signaling formats are much more tolerant of PMD effects compared to NRZ formats. Shieh et al. [8] and Xie et al. [9] have demonstrated a substantial increase in receiver tolerance of DGD when FEC is used. Modern long-haul, 10-Gb/s receivers using FEC or RZ modulation can tolerate about 40 ps of DGD with a 1-dB power penalty.

Probability of signal outage

For occurrences of high instantaneous DGD, signal quality may be intolerable resulting in a PMD-induced outage. Such outages may significantly affect network availability for higher bit rates (10 Gb/s, 40 Gb/s, and higher). For a network to operate with an overall availability of “five nines” (i.e., 99.999% of availability), the desired PMD-related availability factor may be “seven nines” (i.e., 99.99999%) which corresponds to a maximum tolerable DGD 3.7 times the mean DGD. For a 2.5-Gb/s IM-DD NRZ system with a DGD tolerance of 92 ps, this results in an acceptable mean DGD value of 25 ps; for a 10-Gb/s system with a DGD tolerance of 23 ps, the acceptable mean DGD is 6.2 ps; and for 40-Gb/s with a tolerable DGD of 5.7 ps, the acceptable mean DGD level is 1.5 ps. For DGD-tolerant receivers (40 ps at 10 Gb/s) this results in an acceptable mean DGD of 10.8 ps.

Coping with PMD

For network operators faced with the challenge of upgrading the channel data rate on a high-PMD link in the network, a handful of solutions exist that will preserve the signal quality at increased data rates.

One alternative cost solution is to selectively replace those fiber segments in the link known to be the dominant contributors to the overall link DGD, if they can be identified.

Another alternative cost solution is to regenerate the optical signal by placing a back-to-back terminals at the point in the link where the DGD affects approach an intolerable level, thus effectively reducing the optical link length.

Still another approach is to introduce error correction codes, such as FEC. In this approach the optical data payload is reduced incrementally in exchange for a marginal gain in PMD tolerance.

Yet another solution is to incorporate an adaptive PMD compensation system [8, 9, 10, 11, 12], typically located at the receiver. Typical PMD compensation systems are effective at minimizing the effects of first-order PMD, and, in some cases, second-order PMD. However both first- and second-order PMD compensation systems suffer the drawback that they reduce the effects of signal degradation over a very narrow optical bandwidth. This is a significant drawback for dense wavelength-division multiplexing (DWDM) systems. For a long-haul fiber-optic link carrying 100s of wavelengths, a separate PMD compensation system may be required for each wavelength to provide the desired seven nines availability.

For DWDM systems, another potential solution exists. Särkimukka et al. [13] proposed a method for mitigating PMD effects in a multichannel system by moving traffic off of PMD-impaired channels onto spare channels that are not experiencing PMD degradation.

One may also rely upon more traditional protection techniques (e.g. SONET ring or IP routing at layers 1 & 3, respectively). This protection can easily provide a guard against occasional PMD-induced outages of limited duration. However, for this approach to be viable, the episodes of abnormally high DGD events must be infrequent and spectrally localized. To evaluate the feasibility and limits of this solution, an understanding of the temporal and spectral nature of PMD is required.

Finally, there are also efficient optical networking solutions offering varying degrees of protection by using an optical cross-connect with a DWDM system. Operators may then construct a mesh-protected network and provide managed wavelength services that are protected against a possible PMD induced outages. Similar to the traditional protection methods, these more recent techniques will only be viable with infrequent and spectrally localized outages.

TEMPORAL BEHAVIOR OF DGD

Given the dynamic nature of PMD and the low probability of excursions to intolerable levels, measurements of $\Delta\tau(\lambda,t)$

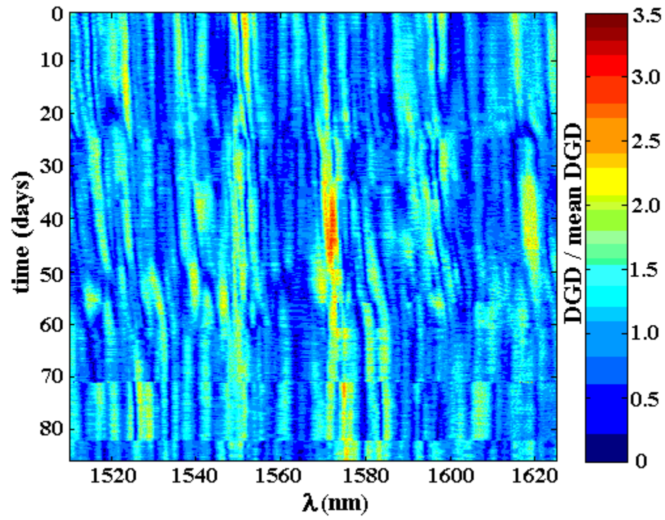

Figure 2. Map of normalized DGD vs. wavelength and time.

on buried fiber spans were made over long periods to enable prediction of the potential impact of PMD on network availability. Of particular interest are the frequency and duration of these rare events. The Jones Matrix Eigenanalysis (JME) technique was used to measure the DGD data on a 95-km span of slotted-core, direct buried fiber-optic cable made available by Sprint.

DGD was measured roughly every 3 hours at wavelengths from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm (about 12.5 GHz). Over 86 days (from November 9, 2001 through February 2, 2002) 692 measurements were made on the 1150 discrete wavelengths. Figure 2 shows in a color-coded format this normalized DGD data (i.e., $\Delta\tau/\langle\Delta\tau\rangle$) representing 795,800 measured values. Expressed another way, if the 0.1-nm spectral samples and 3-hour time samples are statistically independent, then this data set would represent about 272 years of DGD data.

A histogram of this normalized DGD data is shown in Figure 3, and is seen to have shape consistent with a Maxwellian distribution, as expected. A curve representing a Maxwellian distribution normalized to the mean is also plotted for comparison.

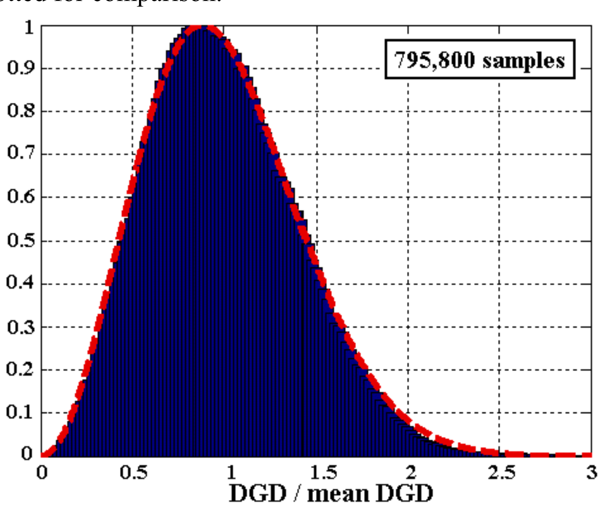

Figure 3. Normalized histogram of measured DGD data.

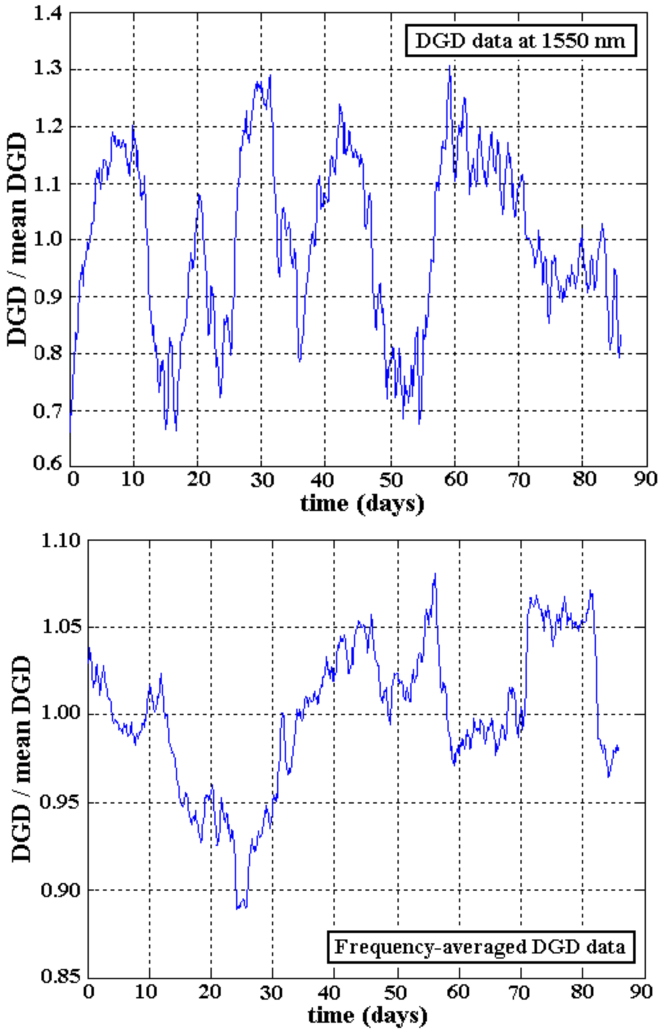

Figure 4. Measured temporal variations in normalized DGD over 86 days (top) at 1550 nm and (bottom) averaged over all 1150 frequency measurements.

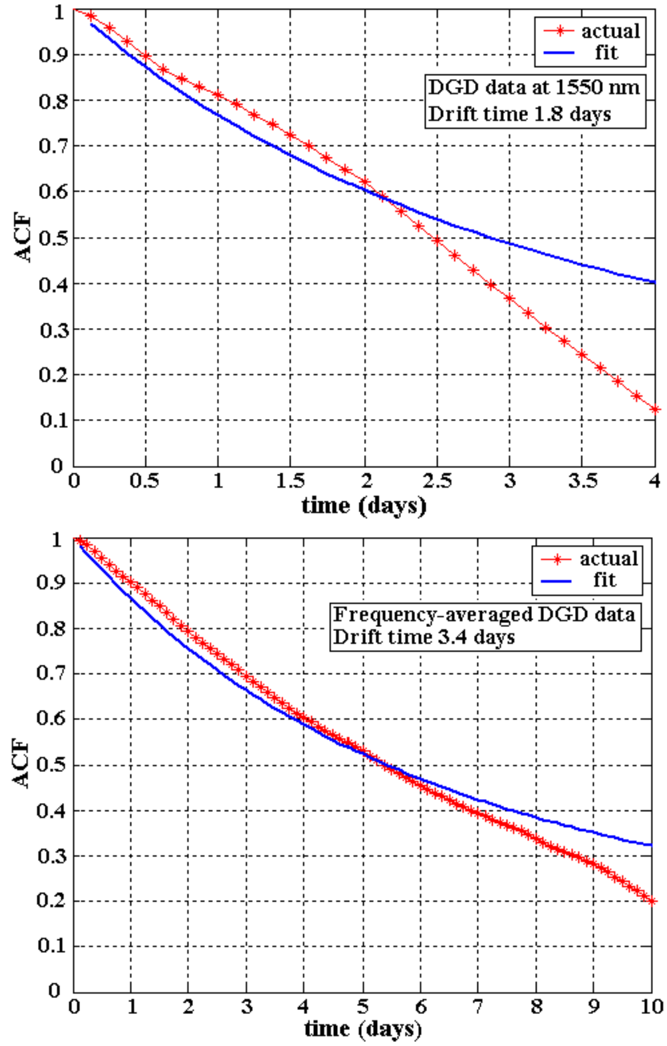

Figure 5. Normalized temporal autocorrelation functions (ACFs) of normalized DGD data measured (top) at 1550 nm and (bottom) across 1150 frequencies. Theoretical ACF curves are fitted to the measured temporal ACFs.

From Figure 2 it is apparent that for buried fiber DGD values do not change rapidly. Figure 4 shows time histories of measured DGD data over the 86-day period. The top plot is DGD data at 1550 nm and the bottom plot is frequency-averaged data. While the mean value of the bottom plot is one (by definition), the mean value of the top plot is 1.088. This should not be interpreted to mean that the mean DGD is changing; rather since fewer data were used to estimate the mean, there is more uncertainty in that estimate compared to the estimate using all of the data.

To determine the DGD rate of change, an autocorrelation analysis was performed on the DGD time histories. Figure 5(top) shows the normalized temporal autocorrelation function (ACF) of the DGD data measured at 1550 nm. Figure 5(bottom) shows the ACF for the DGD time history for the frequency-averaged DGD data. Also shown in Figure 5 are curves representing the theoretical temporal autocorrelation function for DGD [14] which has the form

$$\mathrm{AFC}(\Delta t) = \frac{1-\exp\left(-|\Delta t|/t_d\right)}{|\Delta t|/t_d} \qquad (7)$$

where t_d is the average drift time of DGD. The drift time indicates the timescale over which the DGD changes. Furthermore, when outages occur, the outage duration will be related to the drift time [14,15]. Based on data collected over the 86 days, the drift time for this fiber is estimated to be around 3.4 days. Expressed another way, samples should be collected about once every three days to obtain statistically independent DGD values on a specific wavelength; measurements collected more often are correlated.

For comparison, others have reported a range of DGD correlation times under various fiber conditions. For spools of fiber in a laboratory environment, correlation times of about 30 minutes on 31.6 km of fiber [16] and 3 hours on a 10-km fiber [17] have been reported. DGD variations on a 48-km aerial cable exhibited time scales ranging from 5 to 90 minutes depending the air temperature rate of change [18]. For submarine cables, a DGD correlation time of about an hour was observed on a 119-km cable [19], and [20] observed

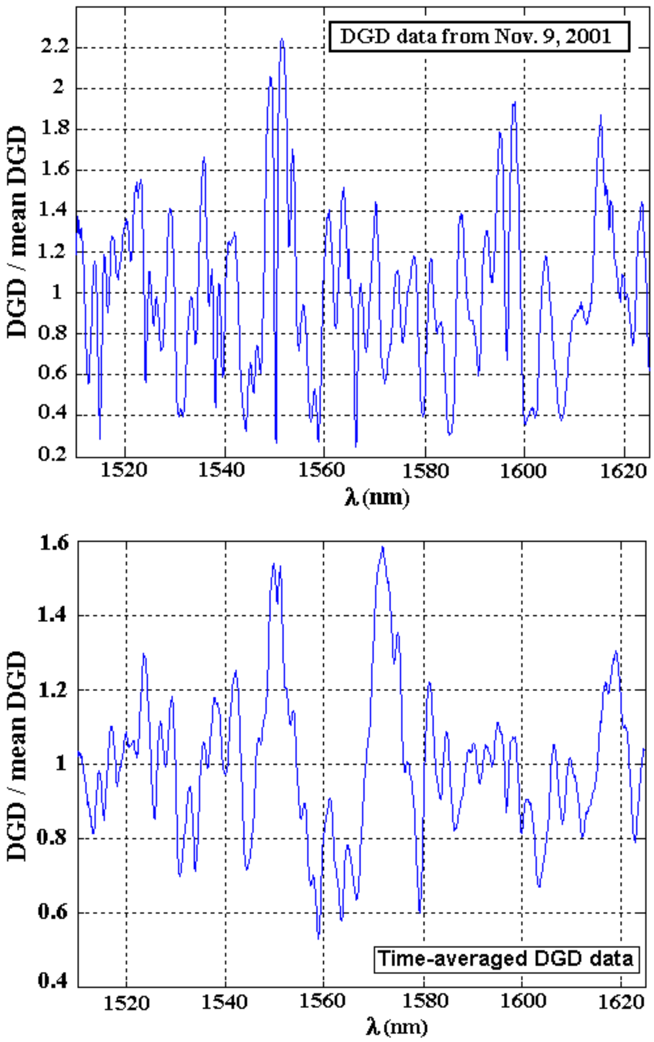

Figure 6. Spectral variations in normalized DGD over 1150 wavelengths (top) measured on Nov. 9, 2001 and (bottom) time-averaged over all 692 time measurements.

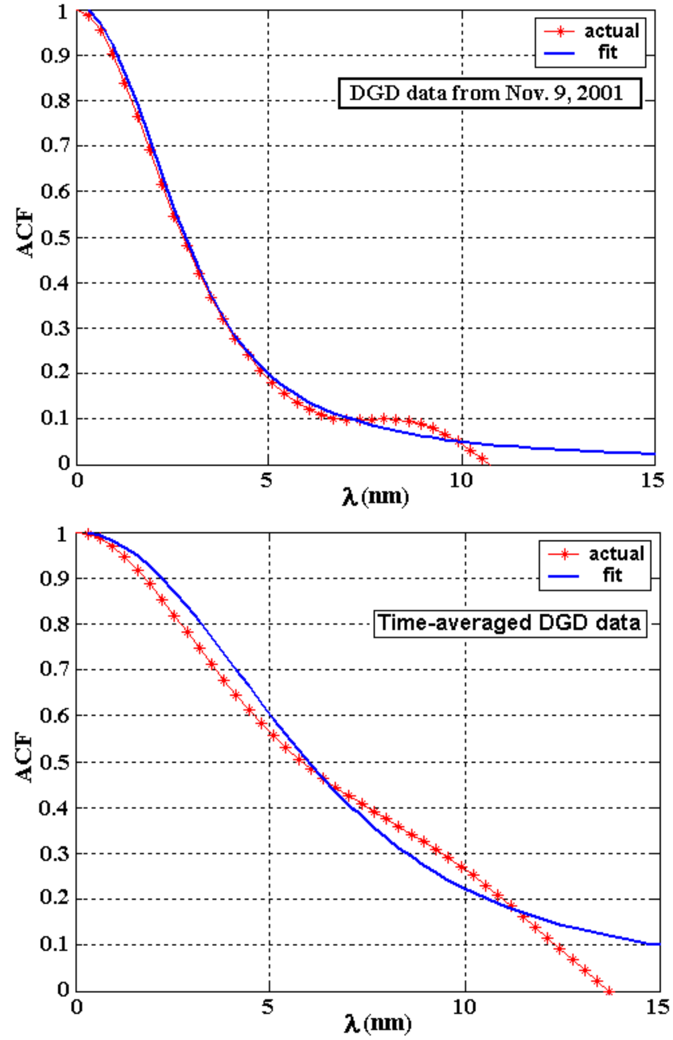

Figure 7. Normalized spectral autocorrelation functions (ACFs) of normalized DGD data measured (top) on Nov. 9, 2001 and (bottom) time-averaged over all 692 measurements. Theoretical ACF curves are fitted to the measured spectral ACFs.

PMD changes with a period of about two months on a 62-km fiber-optic cable. On buried fibers, correlation times of at least 20 minutes (17 km) [21], 1-2 hours (48.8 km) [18], 3 and 5.7 days (127 km) [14], and 19 hours (114 km) [22] have been reported. Thus our observation of 3.4 days is consistent.

With knowledge gained from the ACF analysis, we can now interpret realistically our DGD data set. Over the 86 days of observation, about 25 independent samples were collected.

SPECTRAL BEHAVIOR OF DGD

From Figure 2 we note that the DGD varies significantly with wavelength. Figure 6(top) shows the normalized spectral variation of the first DGD data (measured on Nov. 9,2001) and the bottom plot shows the spectral variation of the time-averaged, normalized DGD data.

To determine the DGD bandwidth, spectral autocorrelation analysis was performed on the normalized DGD spectral data. Figure 7(top) shows the resulting normalized spectral ACF for one spectral measurement (data collected on Nov. 9,2001) and Figure 7(bottom) shows the normalized spectral ACF for the time-averaged data. Also shown in Figure 7 are curves representing theoretical spectral ACFs for DGD, with the form [23]

$$\mathrm{ACF}(\Delta\omega) = 3\frac{1-\exp\left(-\left\langle \Delta\tau^2 \right\rangle \Delta\omega^2/3\right)}{\Delta\omega^2} \qquad (8)$$

where $\Delta\omega$ is the radian frequency and $<\Delta\tau^2>$ represents the variance of the DGD.

From the measured data the bandwidth for the normalized DGD is estimated to be about 7.5 nm or 936 GHz. Therefore if the mean DGD is 1 ps and an optical channel is affected by significant DGD, nearby channels (within about 7.5 nm) may also experience this effect.

Theory and experiments [23] have demonstrated that the DGD bandwidth is inversely proportional to the mean DGD.

$$\omega_c = 4\sqrt{2}/\langle \Delta\tau \rangle \qquad (9)$$

Thus fibers with a high mean DGD have a narrower DGD bandwidth than fibers with a low mean DGD. Thus for a fiber with a mean DGD of 1 ps, the predicted DGD bandwidth is 900 GHz which agrees well with bandwidth found using the spectral ACF fit in Figure 6(bottom). Note that normalized DGD bandwidth in the Figure 6(top) is about 4 nm which is significantly less than the approximately 7.5 nm bandwidth seen in Figure (bottom). This should not be interpreted to mean that the DGD bandwidth is varying; rather the bandwidth estimate obtained using all of the data will be more accurate as it is based on significantly more data points.

IMPLICATIONS FOR NETWORK AVAILABILITY

Mean time between PMD-related outages

The mean time between PMD-related outages can be estimated from the temporal characteristics of DGD variations and the Maxwellian probability density function. The DGD rate of change is characterized by the DGD drift time, t_d. This drift time may be thought of as "rolling the dice" every t_d to obtain a new, statistically independent DGD value. Therefore the mean time between high-DGD events (i.e., DGD exceeding a value X) can be estimated as

$$T_X = t_d / \left(k \cdot P(\Delta\tau > X) \right) \tag{10}$$

where k is a proportionality constant.

For example, Nagel et al. [22] observed a DGD correlation time of 19 hours, and predicts that the DGD will exceed three times its mean value once every 3.5 years. Since the probability of the DGD exceeding three times its mean is about 4.2×10^{-5} we can determine a value of 15 for k.

Applying (10) with a drift time of 3.4 days and a threshold of three times the mean DGD, the mean time between high-DGD events is about 14.8 years. For a PMD-induced outage probability of 1.3×10^{-7} (network availability of seven nines) the receiver should tolerate $3.7\text{x}\langle\Delta\tau\rangle$. With a DGD drift time, t_d, of 3.4 days, the estimated mean time between high-DGD events will be about 4,700 years, making it an extremely rare occurrence!

Duration of high-DGD events

Again from the DGD drift time, the Maxwellian probability density function, and the temporal ACF, the average duration of a high-DGD event can be estimated. While the correlation time represents the time delay resulting in a 63% reduction in the normalized ACF, smaller variations in the ACF require significantly shorter times. Again Nagel et al. [22] estimated a mean outage duration between 10 and 20 minutes for their link having a DGD correlation time of 19 hours. Bülow and Veith [15] found that while unusually long duration outages occur, the probability of occurrence decreases almost exponentially with outage duration. In other words, when outages occur, most will be of short duration.

Based on these findings, for the 95-km link we observed, we anticipate the typical duration of an outage to be between 1 and 2 hours with the possibility that a prolonged outage could persist for 1 to 1.5 days.

Impact of high-DGD events on adjacent channels

When a high-DGD episode occurs, how many DWDM channels will be affected? For a link with a mean DGD of 5 ps, the DGD bandwidth will be about 180 GHz or 1.44 nm. Therefore for a DWDM system with a 50-GHz channel spacing, during a $3.7\times\langle\Delta\tau\rangle$ event, the DGD in adjacent channels may also experience PMD-induced signal degradation, (i.e., only two or three channels will likely be affected by a single high-DGD episode).

Design rules

Based on these observations and analyses, certain rules may be developed. An important parameter in making decisions regarding PMD in a network is the ratio between the receiver's DGD tolerance, $\Delta\tau_{RX}$, and the link's mean DGD.

$$M = \frac{\Delta\tau_{RX}}{\langle\Delta\tau\rangle} \tag{11}$$

For cases where M > 3, the frequency of PMD-induced outages will be low, and their duration may be brief. In these cases the approach proposed by Särkimukka (or one utilizing new protection techniques) may be viable. The occurrences when switching this traffic may be required will likely be infrequent (spanning years), and may only be required for a few minutes or as long as a day.

For cases where 2 < M < 3, PMD-induced outages may occur about once a month with typical durations measured in 10s of minutes.

For cases where M < 2, chronic PMD-induced outages will result. In these instances the option of applying PMD compensation, interrupting the link with a back-to-back terminal regenerator, or even replacing particular fiber segments may be appropriate.

Example scenarios

10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, receiver's DGD tolerance 40 ps

In this scenario the DGD margin, M, is 4. The probability of the DGD exceeding the receiver's DGD tolerance level is about 7.4×10^{-9}, or effectively zero. In this case it is quite unlikely a PMD-induced outage will ever be observed. The DGD bandwidth will be about 90 GHz or about 0.72 nm.

10-Gb/s, $\langle\Delta\tau\rangle$ = 10 ps, receiver's DGD tolerance 23 ps

In this case the margin will be 2.3 meaning that the probability of the DGD exceeding the receiver's limit is about 0.37%. For a buried cable with a DGD drift time of about 2 days, PMD-induced outages typically will occur about once a month and last less than an hour. The DGD bandwidth will again be about 90 GHz.

40-Gb/s, $\langle\Delta\tau\rangle$ = 3.2 ps, receiver's DGD tolerance 5.7 ps

The DGD margin in this case is 1.8 so the probability of the DGD exceeding the receiver's limit is 4.4%. For a link with a drift time of 2 days, PMD-induced outages typically will occur about every third day. The typical duration will be 1 to 2 hours, however outages persisting for a day may occur. The DGD bandwidth is about 2.2 nm or 280 GHz so in a DWDM application with 50 GHz channel spacing, two or three channels may be affected during each outage.

CONCLUSIONS

By examining the statistical behavior of DGD in an optical fiber, and using measured DGD data on a buried optical cable, predictions regarding the probability, frequency of occurrence, and spectral extent of high-DGD episodes can be made. Reports by others confirm our observation that DGD excursions of three or more times the mean DGD are infrequent and relatively short lived. This finding is significant for network operators who may consider providing a few spare channels in a DWDM environment to ensure high network availability.

For cases where the mean DGD is comparable to the receiver's maximum tolerable DGD, approaches for ensuring network availability include inclusion of PMD compensation systems, shortening the link length by strategically introducing back-to-back terminal regenerators, replacing fiber segments found to have excessively high DGD levels, or by utilizing an optical networking solution whereby traffic may efficiently share protection bandwidth.

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REFERENCES

[1] Iannone, E., F. Matera, A. Mecozzi, and M. Settembre, *Nonlinear Optical Communication Networks*, New York: John Wiley & Sons, Inc., pp. 30-35, 1998.

[2] Poole, C. D. and J. Nagel, Chapter 6: "Polarization effects in lightwave systems," in *Optical Fiber Telecommunications III A*, eds. I. P. Kaminow and T. L. Koch, San Diego: Academic Press, 1997.

[3] Betti, S., F. Curti, B. Daino, G. De Marchis, E. Iannone, and F. Matera, "Evolution of the bandwidth of the principal states of polarization in single-mode fibers," *Optics Letters*, 16(7), pp. 467-469, 1991.

[4] Curti, F., B. Daino, G. de Marchis, and F. Matera, "Statistical treatment of the evolution of the principal states of polarization in single-mode fibers," *Journal of Lightwave Technology*, 8, pp. 1162-1166, 1990.

[5] Gisin, N., R. Passy, J. C. Bishoff, and B. Perry, "Experimental investigation of the statistical properties of polarization mode dispersion in single mode fibers," *IEEE Photonics Technology Letters*, 5(7), pp. 819-821, 1993.

[6] Iannone, E., F. Matera, A. Galtarossa, G. Gianello, and M. Schiano, "Effect of polarization dispersion on the performance in IM-DD communication systems," *IEEE Photonics Technology Letters*, 5(10), pp. 1247-1249, 1993.

[7] Khosravani, R. and A. E. Willner, "Comparison of different modulation formats in terrestrial systems with high polarization mode dispersion," *Proc. OFC 2000*, Baltimore, paper WL5, pp. 201-203, 2000.

[8] Shieh, W., H. Haunstein, B. Mckay, D. Fishman, A. Golubchik, J. Diubaldi, C. Martell, V. Arya, R. Lee, and H. Choudhury, "Dynamic polarization-mode-dispersion compensation in WDM systems," *Proc. ECOC 2000*, Munich, Germany Vol. II(4.2.5), pp. 41-43, 2000.

[9] Xie, Y., Q. Yu, L.-S. Yan, O. H. Adamczyk, Z. Pan, S. Lee, A. E. Willner, and C. R. Menyuk, "Enhanced PMD mitigation using forward-error-correction coding and a first-order compensator," *Proc. OFC'2001*, Los Angeles, CA, paper WAA2, 2001.

[10] Rosenfeldt, H., Ch. Knothe, R. Ulrich, E. Brinkmeyer, U. Feiste, C. Schubert, J. Berger, R. Ludwig, H. G. Weber, and A. Ehrhardt, "Automatic PMD compensation at 40 Gbit/s and 80 Gbit/s using a 3-dimensional DOP evaluation for feedback," *Proc. OFC'2001*, Los Angeles, CA, Postdeadline Papers, paper PD27, 2001.

[11] Kikuchi, N., "Analysis of signal degree of polarization degradation used as control signal for optical polarization mode dispersion compensation," *Journal of Lightwave Technology*, 19(4),pp. 480-486, 2001.

[12] Pua, H.Y., K. Peddanarappagari, B. Zhu, C. Allen, K. Demarest, and R. Hui, "An adaptive first-order polarization-mode dispersion compensation system aided by polarization scrambling: theory and demonstration," *Journal of Lightwave Technology*, 18(6), pp. 832-841, 2000.

[13] Särkimukka, S., A. Djupsjöbacka, A. Gavler, and G. Jacobsen, "Mitigation of polarization-mode dispersion in optical multichannel systems," *Journal of Lightwave Technology*, 18(10), pp. 1374-1380, 2000.

[14] Karlsson, M., J. Brentel, and P. A. Andrekson, "Long-term measurement of PMD and polarization drift in installed fibers," *Journal of Lightwave Technology*, 18(7), pp. 941-951, 2000.

[15] Bülow, H. and G. Veith, "Temporal dynamics of error-rate degradation induced by polarization mode dispersion of an installed field fiber link," *Proc. ECOC 1997*, vol. 1, Mo3C, Edinburgh, pp. 115-118, 1997.

[16] Poole, C. D., R. W. Tkach, A. R. Chaplyvy, and D. A. Fishman., "Fading in lightwave systems due to polarization-mode dispersion," *IEEE Photonics Technology Letters*, 3(1), pp. 68-70, 1991.

[17] Bahsoun, S., J. Nagel, and C. Poole, "Measurements of temporal variations in fiber transfer characteristics to 20 GHz due to polarization-mode dispersion," *Proc. ECOC'90*, Amsterdam, The Netherlands, Postdeadline Paper, pp. 1003-1006, 1990.

[18] Cameron, J., L. Chen, X. Bao, and J. Stears, "Time evolution of polarization mode dispersion in optical fibers," *IEEE Photonics Technology Letters*, 10(9), pp. 1265-1267, 1998.

[19] Takahashi, T., T. Imai, and M. Aiki, "Time evolution of polarization mode dispersion in 120 km installed optical submarine cable," *Electronics Letters*, 29(18), pp. 1605-1606, 1993.

[20] Kawazawa, T. and Y. Namihira, "Long-term polarization-mode-dispersion measurement of installed optical submarine cable," *Proceedings of OFC'94*, pp. 228-229, 1994.

[21] De Angelis, C., A. Galratossa, G. Gianello, F. Marera, and M. Schiano, “Time evolution of polarization mode dispersion in long terrestrial links,” *Journal of Lightwave Technology*, 10(5), pp. 552-555, 1992.

[22] Nagel, J. A., M. W. Chbat, L. D. Garrett, J. P. Soigné, N. A. Weaver, B. M. Desthieux, H. Bülow, A. R. McCormick, and R. M. Derosier, “Long-term PMD mitigation at 10 Gb/s and time dynamics over high-PMD installed fiber,” *Proc. ECOC 2000*, Munich, Germany Vol. II(4.2.1), pp. 31-32, 2000.

[23] Karlsson, M. and J. Brentel, “Autocorrelation function of the polarization-mode dispersion vector,” *Optics Letters*, 24(14), pp. 939-941, 1999.