Analysis and comparison of measured DGD data on buried single-mode fibers

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Abstract

Temporal and spectral measurements were made on three different 95-km fibers within a slotted-core, direct buried, standard single-mode fiber-optic cable over many days to characterize DGD variability. From this data we observed that DGD varies slowly over time but rapidly over wavelength. This data showed good agreement with a Maxwellian distribution. The frequency-averaged mean DGD varied by about 10% or less during the periods that included significant temperature swings. Outage analysis showed that for system tolerances of three times the mean DGD, outages will occur typically every 3 to 8 years with mean outage durations ranging from about one to two hours. From this analysis we conclude that high-DGD episodes are spectrally localized and will be exceedingly rare and short lived.

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. While the differential group delay (DGD, or $\Delta\tau$) 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 operating 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. An understanding of the variability of both the DGD and the principal states of polarization (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.

The availability of measured PMD data on installed, buried fibers is limited. In this paper we present measured DGD data for buried, standard single-mode fiber to improve our understanding of the variability of PMD. While PMD is a vector quantity, with a magnitude (DGD) and a direction (PSP), we are only focusing on the DGD. The statistical distribution and behavior of PSPs has been extensively studied and is shown to be correlated to DGD behavior [1,2].

Experimental setup

Experiments were conducted to measure the instantaneous DGD on three different 95-km fibers (1, 2, and 3) within a slotted-core, direct buried, standard single-mode fiber-optic cable made available by Sprint. A polarization analyzer employing the Jones-Matrix-Eigenanalysis (JME) method was used for measurements at wavelengths from 1510 nm to 1625 nm with a spectral resolution of 0.1 nm (about 12.5 GHz). Measurements on fiber span 1 were repeated approximately every 3 hrs and they were carried on for about 86 days whereas on fiber spans 2 and 3 they were repeated approximately every 1½ hours and carried out for about 14 and 9 days, respectively. Over the 86 days (from Nov. 9, 2001 through Feb. 2, 2002) 692 measurements were made on fiber span 1 across the 1150 discrete wavelengths representing 795,800 measured values. For fiber spans 2 and 3 the corresponding number of DGD measurements is about 271,600 and 181,700.

Plots of DGD vs. wavelength and time

Figures 1, 2, and 3 show in a color-coded format normalized DGD data (i.e., DGD/mean DGD) measured on the three fiber spans, respectively. From the plots it is clear that for buried fibers DGD changes with time but not at a rapid rate. This variation is random and differs from fiber to fiber. It is also evident that the DGD varies significantly with wavelength and relatively high-DGD events are spectrally localized.

A histogram of the normalized DGD data on fiber span 1, 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.

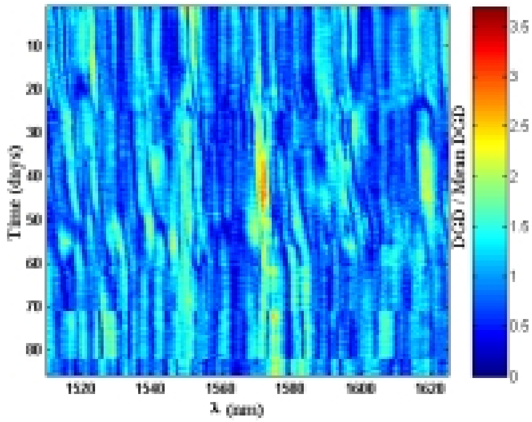


Figure 1. Measured, normalized DGD vs. wavelength and time for fiber span 1 (86 days of data).

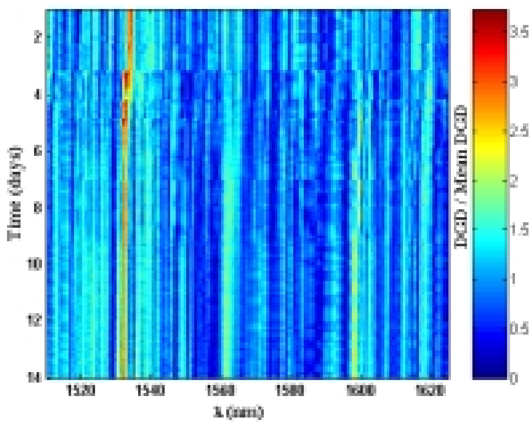
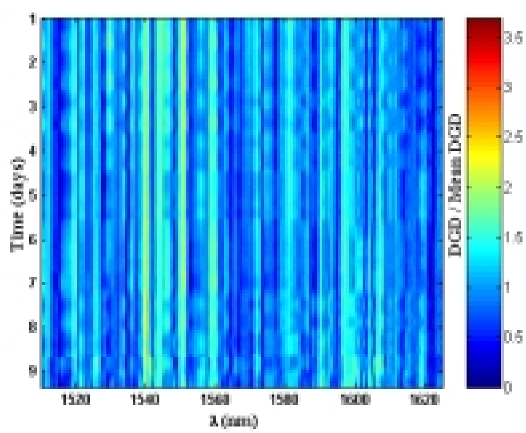


Figure 2. Measured, normalized DGD vs. wavelength and time for fiber span 2 (14 days of data).



(c)

Figure 3. Measured, normalized DGD vs. wavelength and time for fiber span 3 (9 days of data).

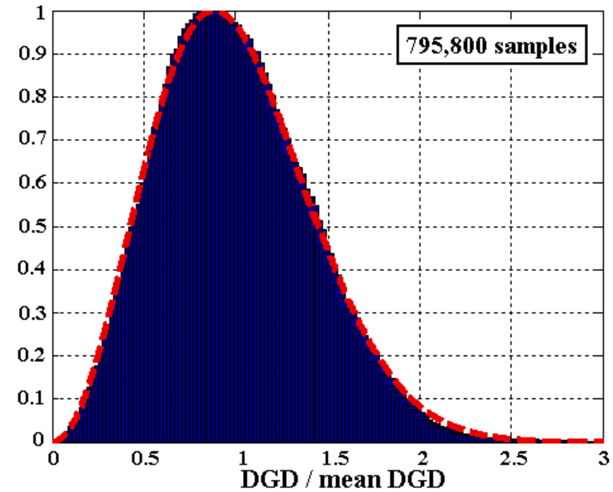


Figure 4. Histogram of measured, normalized DGD data on fiber span 1.

Similar histograms were obtained for the data on the other two fiber spans (plots not shown here) and they also showed good agreement with a Maxwellian distribution.

Mean DGD variation with time

To observe the time-dependent nature of DGD more closely, 1150 DGD measurements over all wavelengths were averaged together to obtain frequency-averaged DGD data, denoted as $\langle DGD \rangle_\lambda$ normalized by the overall mean DGD (averaged over both time and frequency), denoted as $\langle\langle DGD \rangle_\lambda\rangle_t$. Since temperature is a known driver in changing DGD changes, hourly air temperature data for the region were collected as well. The variation of frequency-averaged DGD and temperature with time on the three fiber spans is shown in Figures 5, 6 and 7. From Figure 5 it can be observed that frequency-averaged DGD varies by only about ±10% over 86 days of observations that included significant temperature swings. Since the entire length of the fiber is buried, the diurnal temperature variations do not represent the fiber temperature. Statistical analyses reveal no significant correlation between long-term temperature variations and the frequency-averaged mean DGD.

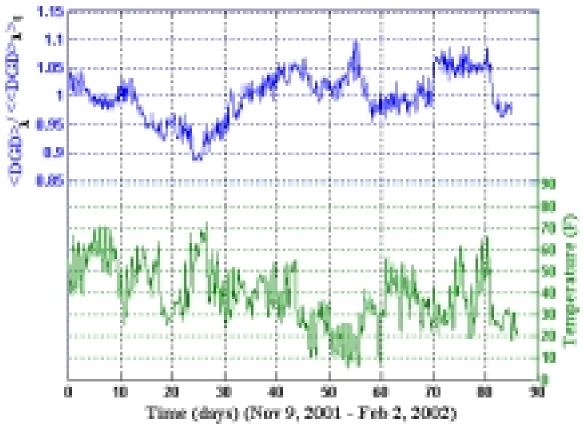


Figure 5. Frequency-averaged DGD and temperature vs. time for fiber span 1.

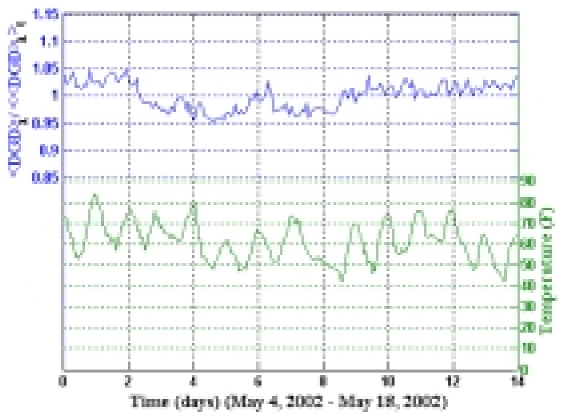


Figure 6. Frequency-averaged DGD and temperature vs. time for fiber span 2.

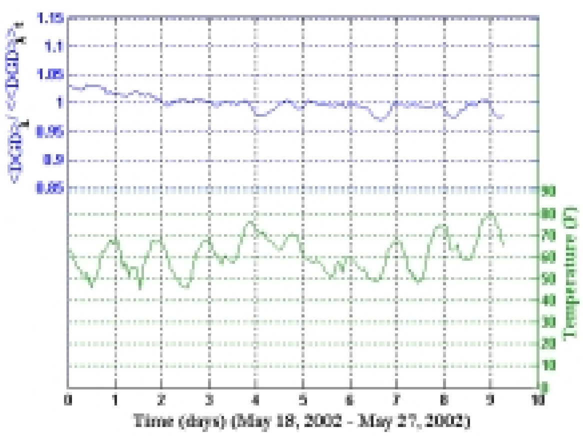


Figure 7. Frequency-averaged DGD and temperature vs. time for fiber span 3.

System outage analysis

An outage event is one which exceeds the given threshold value of DGD, $\Delta\tau_{th}$. The outage probability P_{out}, expressed in minutes/year, can be calculated from the Maxwellian probability distribution function (pdf), $f_\tau(\cdot)$ as

$$P(\Delta\tau \ge \Delta\tau_{th}) = 1 - \int_0^{\Delta\tau_{th}} f_\tau(\Delta\tau)\, d\Delta\tau \qquad (2)$$

and then multiplying the number of minutes in a year. As P_{out} is based on the Maxwellian pdf, it may be expressed as a function of one independent variable M= $\Delta\tau_{th}$/(mean DGD) as $P_{out}(M)$ and is clearly fiber independent and will be the same for all installations.

In cases where the probability of an outage is quite small, P_{out} represents the annualized outage probability based on long time records, however no insight is provided regarding the outage rates and their durations. Accurate estimation of the impact of PMD on network availability requires statistical analysis of the DGD variability. Caponi et al. [3] showed how the mean time between PMD-related outages could be estimated from the temporal characteristics of DGD variations and the Maxwellian probability density function. 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 [3]

$$R_{out} = \frac{1}{2} f_\tau(\text{threshold}) \int_{-\infty}^{\infty} f_{\tau'}(\Delta\tau')\,|\Delta\tau'|\, d\Delta\tau' \qquad (3)$$

where $\Delta\tau'$ is the time derivative of the DGD, and $f_{\tau'}(\cdot)$ is the pdf of $\Delta\tau'$. Caponi et al. observed $\Delta\tau$ and $\Delta\tau'$ to be statistically independent and also found that R_{out} is cable and installation dependent.

Figure 8 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 fiber spans.

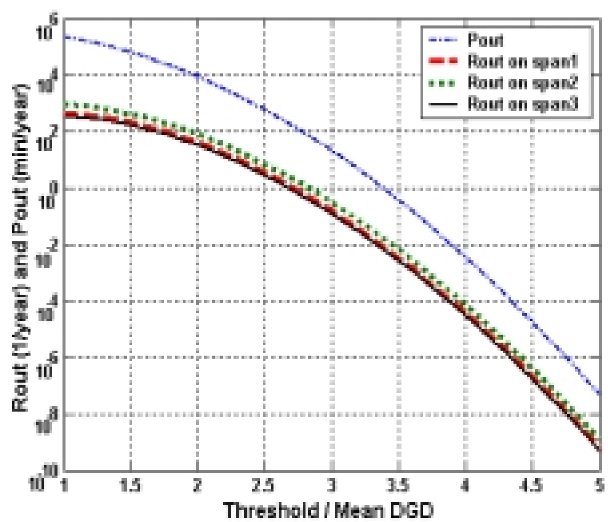


Figure 8. Calculated outage probability, P_{out}, and mean outage rate, R_{out}, versus Threshold/Mean DGD.

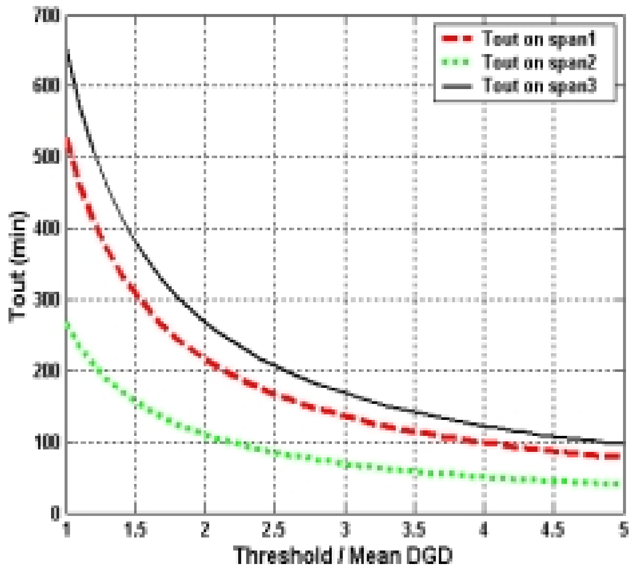


Figure 9. Calculated mean outage duration, T_{out}, as a function of Threshold/mean DGD.

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

	3*<DGD>	3.7*<DGD>
Span 1 MTBO Outage duration	 6.39 years 136 min	 1648 years 108 min
Span 2 MTBO Outage duration	 3.25 years 69 min	 833 years 55 min
Span 3 MTBO Outage duration	 7.91 years 138 min	 2000 years 133 min

The mean duration of DGD-induced outages can be determined using statistical analysis as well. Caponi et al. [3] showed that the mean outage duration, T_{out}, is

$$T_{out} = P_{out} / R_{out} \tag{4}$$

which has units of minutes.

Figure 9 shows the calculated mean outage duration, T_{out}, as a function of system threshold relative to the mean DGD. Since T_{out} is found using R_{out}, which is cable and installation dependent, T_{out} will also be cable and installation dependent.

From the above analysis, we can estimate the mean outage time between outages (MTBOs) and mean outage durations for various DGD tolerances for these fiber spans. Table 1 lists these values for system thresholds of three and 3.7 times the mean DGD.

For comparison, Nagel et al. [4] predicted that for the 114-km buried link they studied, the DGD will exceed three times its mean value once every 3.5 years and estimated a mean outage duration of between 10 and 20 minutes for their link. From data measured on 37-km of buried cable, Caponi [3] predicted the DGD will exceed three times the mean DGD once every 2.5 years with a mean outage duration of 56 minutes.

Conclusions

We have measured DGD data on three different 95-km fibers within a slotted-core, direct buried, standard single-mode fiber-optic. From these measurements we observed that DGD varies slowly over time but rapidly over wavelength or frequency. Episodes of higher-that-average DGD were observed and seen to be spectrally localized and of limited duration.

To investigate the role of changing temperature on mean DGD variations, frequency-averaged DGD data were compared to temperature histories. The frequency-averaged DGD varied by only about ±10% over 86 days of observations that included significant temperature swings.

From this data predictions were made regarding the probability, and frequency of outage occurrence. While the statistics of Maxwellian processes adequately describe the annualized outage probability, further analysis of the DGD data revealed the mean time between outages and mean outage durations. For outages characterized by high DGD episodes (DGD more than three times the mean DGD), we found that the mean outage rates and durations for these three fibers to be similar. Our findings agree with reports by others 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 must assess the impact of PMD on network reliability.

Acknowledgment

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References

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