Polarization mode dispersion compensator field trial and field fiber characterization

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Abstract: Two high-PMD long distance routes were characterized and used to test an optical polarization mode dispersion compensator (PMDC) under field conditions. For this trial, 110 km routes with mean PMD values of 25 and 26.5 ps were provisioned with commercial WDM transport equipment and tested for several weeks. The route was comprised of three spans of characterized fiber that followed railroad tracks. We show the temporal variation of the output polarization state and the evolution of first- and second-order PMD spectra over 7 days. The deployment of a variable-length PMDC on these links allowed error-free transmission of an OC-192 signal. Splitting the output to receivers with and without PMDC demonstrated specific PMD events that caused errors in the absence of a PMDC.

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Introduction
Polarization mode dispersion (PMD) represents a major impairment for optical systems operating at high bit rates such as 10 Gb/s or higher. PMD arises when the circular symmetry of the fiber is broken either by externally induced stress from the environment or during the manufacturing process. Based on field measurements, high PMD is mostly found in fiber manufactured before the early to mid 1990s. System and route designers must consider PMD when designing higher bit-rate systems operating at 40 Gb/s. For some routes, even the 10 Gb/s bit rate will experience intolerable intersymbol interference errors due to PMD. Optical PMD compensators must actively track the direction and magnitude of the PMD vector during operation. Thus, understanding the temporal nature of these changes is useful since the rates of change set requirements on PMDC tracking speeds. We measure directly the
Temporal evolution of the magnitude of the first and second order DGD and infer the rate of change in the direction of the PMD vector by measuring the rate of change in the state of polarization (SOP), as suggest by [6]. By quantifying these changes, we gain a better understanding of performance requirements, and are able to more realistically test PMD compensators in the lab. Importantly, this paper also reports the performance of a variable delay PMD compensator installed on a three span, 110 km route where most of the route is adjacent to railroad tracks.

**Fiber Characterization**

A 110 km route of three spans (36.6 km, 36.5 km, 37.3 km) of high PMD fiber manufactured in 1994 was selected for this site. First, PDL measurements were performed on each fiber by launching polarization-scrambled monochromatic light into each fiber and monitoring the output with a polarimeter. Measurements were made over ~ 5 minutes (to provided significant coverage of all input polarization states). The PDL measured for all fibers was less than 0.5 dB.

PMD of each fiber was measured using the interferometric method. Broadband light was input to each fiber and the PMD measured separately on each fiber for every span. The mean PMD from 5 measurements on each fiber is listed below in table 1. We assume that the line equipment (such as EDFAs, DCMs, mux/demux optics) contributed a PMD of 3 ps. The total mean system PMD, including fiber and components, is calculated using root-sum-of-squares, to yield route PMDs of 25 ps and 26.5 ps.

| Link # | Span 1 PMD | Span 2 PMD | Span 3 PMD | Total Fiber PMD | Component PMD | Route PMD |
|--------|-------------|-------------|-------------|-----------------|---------------|-----------|
| 1      | <9 ps>      | <11.2 ps>   | <20.1 ps>   | <24.7 ps>       | <3 ps>        | <25 ps>   |
| 2      | <8.5 ps>    | <10.2 ps>   | <22.7 ps>   | <26.3 ps>       | <3 ps>        | <26.5 ps> |

Table 1. Link PMD data taken with the interferometric PMD field unit

Two fibers from one span were looped back through an EDFA at the midpoint and connected to a tunable laser on one end and a Stokes polarimeter on the other. With the laser and polarimeter collocated, we were able to make PMD measurements using Jones Matrix Eigenanalysis (JME) to obtain the instantaneous differential group delay (DGD) at various wavelengths [1]. We also performed appropriate derivatives to obtain second-order PMD (SOPMD) magnitudes across the spectrum [1]. We performed these measurements on two occasions, on different fiber pairs. For the first measurement, we took JME data over a 30 nm range, using 20 pm steps. The spectral scans were repeated every 2.5 hours, for a total of 160 hours. The DGD and magnitude of SOPMD are shown in Figure 1. A file showing the time evolution of this spectrum is provided as file spectrum1.mov (Fig 1. C). We repeated the measurement on a second fiber pair. Here a 20 nm range (20 pm steps) was measured every 1.6 hours for 174 hours, and the result shown in Figures 2 and as file spectrum2.mov (Fig 2. C). Based on laboratory measurements on artifacts with known DGD and SOPMD [2], we estimate that the instantaneous PMD values in these plots has better than 10% uncertainty. Of particular interest are the abrupt changes across the spectrum (~145 hours in Figure 1 and ~ 80 hours in Figure 2) that occurred much faster than our measurement period. These abrupt changes occur occasionally but we were unable to correlate to any events along the route, and this type of behavior merits additional investigation.
Fig. 1.A) DGD as a function of wavelength and time for a fiber pair on span 3.

Fig. 1.B) SOPMD as a function of wavelength and time for a fiber pair on span 3.

Fig. 1.C) Spectrum movie of 160 hours – spectrum1.mov (1.278 KB)
Fig. 2.A) DGD as a function of wavelength and time for a second fiber pair.

Fig. 2.B) SOPMD as a function of wavelength and time for a second fiber pair.

Fig. 2.C) Spectrum movie of 174 hours – spectrum2.mov (1.904 KB)
The changes in the polarization state after propagation was measured for two cases by launching light with a fixed polarization and detecting the output with a commercial polarimeter. The polarimeter logs data at a rather low rate, but has analog output ports that provide Stokes parameter values at a 4 kHz update rate. We used A/D boards and a data acquisition program to gather this data for extended periods.

First, we measured a fiber on the middle span with 18 ps PMD and a length of 36.5 km. SOP data was acquired at 4 kHz for 14.7 hours (gathering a total of 42.2 M samples). A second measurement was made along link #1 (3 spans with two midspan EDFAs, with 25 ps PMD over 110 km). Here we acquired 9 hours of data at 4 kHz.

![Fig 3. Histogram of SOP excursions for link #1](image)

To present this large amount of data, we partitioned the time series into bins of 1 ms and calculated the largest SOP change by calculating the angle on the Poincare sphere for the most separated two points in each bin. We then formed histograms plotting number of occurrences for each maximum excursion [3]. Figure 3 shows the histogram from the 110 km fiber link measurement.

Detailed analysis of the data showed several rare events that have very large polarization changes. These are surprising because they do not follow a smooth, continuous function, but rather they suggest discontinuous jumps in polarization that do not seem physical. We investigated this issue by measuring the values of S1, S2, S3 and DOP acquired from the polarimeter while measuring the polarization changes from a laboratory polarization scrambler. We acquired 50,000 points, and found several instances of an instrument glitch in the polarimeter output; Figure 4 shows 25 ms of data (100 measurements) representative of this effect.
Most of the data shows variation with time similar to that seen from samples 50 to 100. Occasionally, however, we see short times over which the recorded is constant (for example, samples 30 to 45 above). During these hold times, all values are fixed for ~ 4 ms. At the end of this period, the recorded value abruptly changes, and gives a value close to that we’d expect if the data were extrapolated over the hold time. Having all Stokes parameters and DOP simultaneously fixed during scrambling is highly improbable, so these artificial jumps due to this instrument were removed by carefully excluding these outage regions in out data analysis. As a result the rare but unusually large polarization changes seen in Figure 3 that resulted in the very extended tail in the SOP distribution were removed. Histograms of filtered data from the fiber plant measurements are shown in Figures 5a and 5b. Also shown are the excursion angles that encompass 99%, 99.9%, and 99.99% of occurrences.
Test Bed and Experimental Setup

After the fiber characterization, a 1+1 bi-directional OC-192 system was installed on two fibers using a commercially available transport system. A diagram of one link, showing three spans and two mid-span amplifier sites, is shown in Figure 6. The amplifier system carried one chirped NRZ OC-192 wavelength in each direction. Chromatic dispersion compensation modules (CDCM) were placed at both mid-span sites to limit the residual chromatic dispersion to ~ 400 ps/nm. At each fiber input, optical powers of 7.5 dBm or less was launched at each wavelength. Receiver powers ranged from -7.5 to –6.5 dBm. Power levels fluctuated about 0.1 dB during the trial. No forward error correction was used during the tests. Bit error-rate (BER) performance was measured using the raw SONET data stream.

Previous field tests of PMD compensation measured performance by sequentially switching the PMDC in and out of the path [4-5]. Since the distortion changes with time, such methods are not necessarily a direct comparison. We performed simultaneous comparisons using a modification used at one terminal of one link to directly evaluate the performance of the PMD compensator (Figure 6). Light exiting the link after distortion due to PMD, chromatic dispersions, ASE noise, etc., is split through a 60/40 splitter so that the compensated and uncompensated receivers can be monitored simultaneously. Attenuators were placed at the receivers so both received ~7 dBm optical power. This is important because although the fiber PMD is known, the instantaneous DGD and SOPMD will vary with time but cannot be easily measured while transmitting data. In this test, both receivers detect the same distorted signals, and instances of PMD-induced degradation will cause errors only in the uncompensated receiver if the PMD compensator is effective. Thus we can obtain a fair comparison of compensated and uncompensated receivers.

We used this route to test the efficiency of an optical PMD compensator. The device consists of a polarization controller followed by a variable DGD element, and can compensate greater than 100 ps of DGD. A small fraction of the light exiting the variable DGD is detected to determine the degradation of the 10 Gb/s data channel. This signal is used for feedback by a control algorithm in a digital signal processor. The algorithm adjusts the
polarization controller and DGD elements in real-time to track polarization and fiber PMD and minimize degradation in the 10 Gb/s data stream.

Two BER test sets monitored the OC-12 and OC-48 tributaries off of each OC-192 receiver, compensated and uncompensated, for 25 days. During this time, the receiver without PMD compensation receiver lost synchronization during three separate instances; one event of 17 severely-errored-seconds (SES) on day 2, 12 SES on day 7, and a 10 SES event on day 17. During these events the receiver using PMD compensation remained error free. The second link, which did not use the split-receiver configuration, ran error-free with PMD compensation for 25 days.

Conclusion

Measurements on buried fiber showed the evolution of instantaneous DGD and SOPMD spectra on high PMD fiber. DGD changes on the order of 10 ps/hr were common; very abrupt changes faster than the measurement time also occurred, and these require more study (using faster measurement methods, or scans over smaller wavelength ranges) to understand the rates of these changes. Changes in SOP were also quantified, and these data can be used to compare with commercial polarization scramblers so that PMD compensators can be realistically tested in the laboratory.

An optical PMD compensator was tested using chirped NRZ OC-192 signals and shown to effectively reduce outages due to PMD. A two-receiver configuration was used to directly compare the bit-error-rate performance of receivers detecting the same signal with and without PMD compensation. Over 25 days, the uncompensated receiver took three traffic-disrupting events while the PMD compensated receiver did not.

This method of testing is desirable since PMD is a statistical phenomena and it’s instantaneous values are difficult to obtain in field conditions on traffic-carrying fiber. PMD describes a mean DGD over all wavelengths, but at a given wavelength the actual DGD may be small (and remain small for an extended time) so the resulting signal distortion may minimal and not affect BER. Alternatively, distortion may be minimal if the launch SOP is closely aligned with a principal state. Direct comparison of BER with and without PMD compensation on the same signal allow effective performance evaluation with high confidence.