PMD Tolerance Testing of a Commercial Communication System Using a Spectral Polarimeter

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Abstract—A stress study methodology for polarization-mode dispersion (PMD) tolerance testing of commercial telecommunication systems is reported. By inserting additional PMD and using intralink polarization scrambling, multiple configurations of the fiber parameter space are sampled. By monitoring both the preferential-error-correction bit error rates and the spectrally resolved states of polarization or string lengths, the error rates are correlated with the PMD-induced system degradation, and it is shown that it is not correlated with power or optical signal-to-noise-ratio fluctuations. Configurations with the PMD uniformly distributed across the link and lumped at the transmitter or receiver ends are also compared.

Index Terms—Optical fiber communications, polarimetry, polarization-mode dispersion (PMD), system performance.

I. INTRODUCTION

MODERN telecommunication systems are intelligent, complex, and organized as a hierarchy of logical levels. They also employ many sophisticated feedback mechanisms. All these properties are necessary for maintaining an optimal operating point for data channels that suffer from a set of impairments. These impairments include amplified spontaneous emission (ASE) noise, chromatic dispersion, inter- and intrachannel nonlinearities, polarization-dependent gains and loss, and polarization mode dispersion (PMD). The last two stand apart from the other impairments due to their intrinsically random nature that is independent of the mode of measurement.

This randomness creates a twofold difficulty for PMD mitigation: It complicates consistent testing of the PMD tolerance of a link and makes it hard to collect the statistics of PMD-induced penalty for estimating outage probability. In this paper, we address both of these issues. First, we use a spectral polarimeter [1] to correlate the observed bit error rates (BERs) with the spectral state of polarization (SOP) “string” length, which is a measure of frequency dependence of the polarization at the receiver (Rx). Here, the SOP string length (SOPL) represents the length of the wavelength-dependent SOP trace on the Poincaré sphere over the modulation bandwidth of the channel. Second, we use the PMD-stress test similar to that in [2] as a tool to estimate the performance of a commercial system with a large amount of PMD inserted into the link in three different configurations.

For testing purposes, it is impractical to wait until a high-PMD effect occurs naturally in a real system, and PMD emulators are sometimes used to create such occurrences. At the same time, there is no standard procedure for emulation of these high-PMD events. Even more sophisticated “all-order” emulators [3] provide PMD that is “lumped” in one location in an optical line. Time scales for polarization variations of high-PMD events are influenced by many factors. Outside temperature drifts cause daily variations [4]–[6]; temperature variations in air-conditioned amplifier huts may cause hourly variations [7], [8]; and a technical crew can move the fiber over several seconds. These are predominant sources of PMD-penalty variations. However, submillisecond polarization fluctuations have also been detected in field-installed systems [9], [10], and bit-pattern-dependent nonlinear interaction has been shown to cause polarization rotation at rates comparable to the bit rates [11], [12]. In the presence of multiple impairments, BER, optical power, and optical signal-to-noise ratio (OSNR) measures are not enough to isolate polarization-related problems in the link.

It follows that it is useful to evaluate the impact of PMD on optical communications systems separately from other impairments. Several PMD-related measures have been used for PMD-penalty estimation. These include the degree of polarization (DOP), the RF spectrum, and the eye opening, which have been reviewed [13]–[15]. Although related to the string length, the DOP has been shown to be sensitive to ASE noise and, therefore, dependent on the OSNR level of the signal. Other methods require expensive equipment such as RF spectrum analyzers and gigahertz oscilloscopes. The eye-diagram measure is costly to implement at or above 40 Gb/s, addresses only one channel at a time, and does not efficiently differentiate the penalty due to PMD from other performance degradations. Recently, the SOPL [16] has been demonstrated to have a strong correlation with PMD-induced penalty in a channel. In this paper, we demonstrate the estimation of PMD-induced system degradation from direct measurements of the...
SOPL at the Rx end using a high-speed high-spectral-resolution polarimeter [1], together with a high-mean-PMD scrambled test. The millisecond sensing speed and high-spectral-resolution capabilities of the spectral resolution are necessary to resolve both the temporal and spectral dependence of the SOP within a dense wavelength-division multiplexing (DWDM) channel. The SOPL measurement capability of the spectral polarimeter has also been demonstrated on a commercial system carrying live data traffic [17].

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. Measurements are carried out on a commercial 10-Gb/s nonreturn-to-zero (NRZ) line system (Nortel common photonic layer). The C-band wavelength-division-multiplexed spectrum consists of nine groups of eight wavelengths. The groups are separated by 100-GHz guard bands, and the wavelengths are separated by 50 GHz. The test group comprises seven wavelength-adjacent electronically dispersed precompensating transmitters (Nortel eDCOs), which are configured to transmit a $2^{31} - 1$ pseudorandom binary sequence (PRBS) data pattern. The eDCOs are polarized aligned at the transmit side of the link, and the launch polarization of the group is set by another polarization controller. The balance of the spectrum (65 channels) is occupied by continuous wave sources (with ILX SSB 9200 occupying the odd channels of the International Telecommunications Union grid and Profile 8000 occupying the even channels), whose purpose is to load the amplifiers.

All of the transmit-side wavelengths are partially combined with disparate channel MUX equipment and then further combined and power equalized with a 50-GHz multiprot wavelength-selective switch (WSS). The resulting spectrum is launched into a 20-span link of an 80-km-long standard G.652 fiber with an aggregated mean differential group delay (DGD) of 7.3 ps. Each of the 80-km segment is loss padded at the receive side to 21 dB. The average pad value is 4.5 dB. The losses in each span are compensated using single-stage amplifiers (∼5.5 dB noise figure), and there is no optical compensation for dispersion. Power conditioning within the link is provided by voltage-controlled attenuators within buffered group MUX/DEMUX filter pairs and by a second WSS proximate to the optical loop back. Preforward error correction (FEC) BERs were recorded at 1-s intervals on seven channels.

Six automatic polarization controllers are distributed in the fiber link before fiber span numbers 1, 4, 9, 12, 15, and 19 to emulate the “hinge” model [7], [18]. To amplify the amount of PMD effects, six sections of high-PMD fibers are distributed into spans following the polarization controllers, and the values of their mean DGDs were 30, 5, 10, 10, 10, and 19 ps, respectively, achieving a total mean DGD of ∼40 ps within the link. In two alternative configurations, all the PMD elements, which are still separated by polarization controllers, were also lumped together either after the transmitter (Tx) or before the Rx. Note that this level of PMD is two to three times higher than that for a typical NRZ system with a mean DGD of about 15% of the bit duration.

At the end of the 1600-km fiber link, 5% of the signal is tapped for spectral SOP measurements, which are carried out with a custom-made high-speed high-spectral-resolution polarimeter [1]. The spectral polarimeter has two main parts, as shown in Fig. 2. The first part is a fast polarization analyzer comprised of a pair of ferroelectric-liquid-crystal switchable quarter-waveplates and a fixed polarizer, which allows millisecond-response polarimetry [1]. The second part of the polarimeter utilizes a virtually imaged phased array (VIPA) [19] and an InGaAs line-scan camera that was used as a detector array, which allows wavelength-parallel SOP measurements. The VIPA was used instead of a diffraction grating because of its much larger angular dispersion compared to that of a grating [20], which is necessary to resolve the SOP pattern within a 10-Gb/s DWDM channel bandwidth. The VIPA (which was donated by Avanex) in this experiment has a free spectral range (FSR) of 50 GHz, which was designed to match the channel spacing. From the detector array, we use 128 pixels with a 50-µm pitch and 100-µm pixel spacing, 80 of which are covered by the 50-GHz FSR of the VIPA, and the 3-dB spectral resolution at the camera aperture is roughly 1 GHz. However, due to the periodic dispersion property of the VIPA, a tunable filter with a 3-dB passband of 32 GHz and 25-dB suppression of adjacent channels is used before the polarimeter for performing multichannel measurements. Although not implemented in this experiment, if high-speed monitoring of large numbers of channels is desired, one could opt for the multichannel high-resolution spectral polarimeter described in [21]. This novel spectral polarimeter design is suitable for parallel spectral SOP measurements for all channels within the entire C-band and with the same high spectral resolution.

Each pixel spacing of 100 µm corresponds to approximately 0.63 GHz, and 17 consecutive pixels were taken to cover ∼10 GHz of the 10-Gb/s NRZ modulation bandwidth, with the ninth pixel on the carrier frequency. The SOPL is calculated as
Fig. 3. Sample SOP strings measured over a 10-GHz bandwidth. (a) SOPL = 2.7 rad, experiencing near first-order PMD (b) SOPL = 1.75 rad, experiencing high-order PMD.

the sum of the arc distance between each of the neighboring spectral SOP pairs and is measured in radians as

\[
SOPL = \sum_{i=k-8}^{k+8} \arcsin (|\hat{s}_i \times \hat{s}_{i+1}|)
\] (1)

where \(k\) is the pixel number of the center frequency, and \(\hat{s}_i\) is the normalized Stokes vector of the frequency designated at pixel \(i\). The SOPL measurements have an uncertainty of approximately 0.062 rad, which is estimated by the standard deviations (STDs) of 15 measurements of a steady SOP string and averaged for ten different strings with different lengths. Samples of the measured strings are shown in Fig. 3. As can be seen, a 10-GHz bandwidth is well resolved by the polarimeter. Parallel to the spectral polarimeter, a commercial Thorlabs PAT9000 polarimeter is used to monitor the average SOP and DOP of each of the channels and at the same time to corroborate the spectral polarimeter measurement results.

III. MEASUREMENTS AND RESULTS

Measurements were taken from seven channels ranging from 1530.33 nm (195.9 THz) to 1532.68 nm (195.6 THz). Pre-FEC BERs from a 2\(^{31}\)−1 PRBS pattern were recorded in 1-s intervals from all seven line cards. Spectral SOP measurements were cycled through the seven channels at a rate of roughly 3 s per channel for 19 h. The six polarization controllers distributed within the fiber link were randomly switched at the end of each cycle to imitate the statistics of five active PMD “hinges,” which are consistent with the hinge-number estimation in [7], and to launch SOP variations. The 3-s interval insures that at least one full second of BER was collected during the stable states of the polarization controllers between switching and allows the optical bandpass filter preceding the polarimeter to settle. The numbers of samples taken at each channel for the three high-PMD distribution configurations were 1842 for the distributed PMD, 1542 for the PMD lumped at Tx, and 462 for PMD lumped at Rx.

Using the power spectral measurement capability of the polarimeter, we also monitored total power and OSNR. To obtain the power spectrum of a signal, two orthogonal polarization components (i.e., 0° and 90°) measured by the polarimeter were summed. Fig. 4(a) shows a sample of the normalized spectral profile of a tested OC192 channel, which was measured by the spectral polarimeter. Power readings from 31 pixels centered at the carrier-frequency pixel can be summed to obtain the total power of the signal region above the noise floor. Due to slight polarization dependence of the power readings of the orthogonal polarization components [22], the accuracy of the total power measurement is polarization dependent and has an error with an STD of \(\sim 0.19\) dB, which was obtained from an independent study. The OSNR can be calculated by taking the difference between the peak power and the noise floor. The noise floor is shaped by a combination of passbands of both the tunable filter and the VIPA and is approximately Gaussian. The log scale of the noise floor can be approximated with a quadratic fit to the data in decibels. Due to the pixilation of the measurements, the signal peak may land in the middle of a pixel, as shown in Fig. 4(b), or it may not, resulting in the peak power splitting among two neighboring pixels, as shown in Fig. 4(c). This problem can be alleviated by best fitting the top three power readings with a quadratic fit to better approximate the signal peak. This technique does not give a perfect measurement of the absolute OSNR but is rather a tool for monitoring the relative fluctuations in the OSNR of the system that are within an accuracy of 0.23 dB (STD). This accuracy evaluation was done through independent verification by comparing the OSNR measurements obtained from an OSA with those from the polarimeter. The range of OSNRs that can be measured depends on the dynamic range of the camera; a typical 12-bit camera can measure up to 33 dB. It is also worth noticing that the OSNR measured here uses a bandwidth of one-pixel width or equivalently 0.63 GHz (\(\sim 5\) pm), which results in higher OSNR readings compared to measurements with the
standardized 0.1-nm bandwidth. The mean values of measured BER, SOPL, OSNR, and DOP are shown in Fig. 5, and the error bars represent their STDs; these figures will be referred to in later comparison tests. The downward OSNR and DOP shift in Fig. 5(c) and (d), respectively, resulted from a change in the amplifier setting at the monitor arm of our setup for one of the PMD layout configurations, which did not affect the BER of the system.

Fig. 6(a) displays the BER versus SOPL relationship taken from one of the channels measured for the PMD-distributed configuration. It is apparent that a strong correlation exists, and the relationship is well represented by a quadratic curve. The data points have a Gaussian scattering centered at the quadratic curve with the STDs ranging from 0.109 dB for the best channel to 0.158 dB for the worst. An averaged STD of 0.128 dB from seven channels of all three PMD configurations is shown in the inset of Fig. 6(a). The OSNR and total power of the same sample channel used in Fig. 6(a) were also compared with the respective BER scattering data of that channel and is plotted in Fig. 6(b). OSNR and total power versus BER scattering have averaged correlation coefficients of 0.062 and 0.0015, respectively, for all channels and configurations, indicating that there are nearly no correlations and rendering the errors in the SOPL measurement and high-order PMD as the main cause of the scattering [23]. Fig. 6(c) shows best fit curves for all seven channels of the three PMD distribution configurations. It can be seen that the curvatures of the 21 traces do not change much; only the vertical positions of the traces change and are determined by other system penalties of each channel. To show that all three different PMD configurations yield the same SOPL versus \( \log_{10}(BER) \) relationship, we plotted the best fitted \( \Delta \log_{10}(BER) \) versus SOPL, which was averaged over seven channels for each of the three PMD distribution configurations, where \( \Delta \log_{10}(BER) = \log_{10}(BER) - \log_{10}(BER(SOPL=0)) \). As can be seen, there is little or no difference in the curvature. This is expected in a system operating in the linear regime, which is a requirement for the successful operation of the electronically dispersed precompensated system [24], [25].

We emphasize that the system was operating at a mean DGD of \( \sim 40 \) ps, which is two to three times higher than a standard 10-Gb/s RZ system’s mean DGD limit (about 15% of the bit duration). Such a stress test allows easy assessment of the performance under high-PMD effect. Note also that this test may somewhat overestimate the PMD impact on the system. Indeed, since the higher orders of PMD are correlated to both instantaneous and mean PMD [26], we expect the contributions to PMD degradation from higher orders to be overestimated.

The probability density functions of \( \log_{10}(BER) \) for the best and the worst channels are plotted in Fig. 7. Note that the long tail only prolongs to the \( 10^{-5} \) levels, even under stressed conditions.

We observed that the statistics of the SOPL measured by our polarimeter is different from the Rayleigh distribution of SOPL due to the first-order PMD reported in [16]. By definition

\[
SOPL = \int |dS(\omega)/d\omega| d\omega = \int |\tau_\perp(\omega)| d\omega
\]

where \( S(\omega) \) is the normalized Stokes vector at frequency \( \omega \), and \( \tau_\perp(\omega) \) is the length of the component of the input PMD vector perpendicular to the launch Stokes vector. The SOPL calculated from this equation only leads to a Rayleigh
distribution for first-order PMD approximation, meaning either for a very small integration bandwidth or for constant PMD over the integration bandwidth. The complementary cumulative distribution functions (1-CDFs) of the SOPL we measured over 2.5- and 10-GHz bandwidths are plotted in Fig. 8. These distribution curves are obtained from the data of all seven channels for all three PMD distribution configurations, totaling to more than 25 000 fiber settings. Theoretical traces of Rayleigh distributions that share the same mean values with their respective SOPL sets are also plotted in the same figures for comparison. As previously mentioned, the deviation from the Rayleigh shape for SOPL of finite bandwidths seen in the figures is a manifestation of the higher order PMD present in the system under test. By comparing the insets of Fig. 8(a) and (b), it can be observed that the probability density of the SOPL deviates more evidently from the Rayleigh shape as the bandwidth of the SOPL increases from 2.5 to 10 GHz. We also attribute the downward deviation in the longer string length regions of the complementary CDFs to the finite number of hinges implemented in the system.

As a comparison of the performance of estimating PMD degradations using SOPL and another common method DOP, we plotted the correlation between BER and DOP measurements collected using the commercial polarimeter and taken simultaneously with the SOPL measurements shown in Fig. 6. As shown in Fig. 9(a), there is an approximately linear relationship between DOP and log (BER). The BER scattering in this case is larger than those observed in Fig. 6(a) and has an averaged STD of 0.203 dB, ranging from 0.157 dB for the best channel to 0.235 dB for the worst. Part of the scattering is due to the power dependence of this method, as shown in Fig. 9(b), and the correlation coefficients of the scattering plotted with the OSNR and total power are 0.44 and 0.37, respectively. This demonstrates that the SOPL is better for estimating PMD-induced penalty. Note the downward shift in the OSNR curve of the PMD-lumped-at-Rx configuration plotted in the Fig. 5(c), which resulted from a change in the amplifier setting at the monitor arm of our setup as previously mentioned. The fitted curves of the DOP method for every channel shown in Fig. 9(c) significantly shifted for that particular configuration, while the fitted curves of the same configuration using the string-length method shown in Fig. 6(c) did not vary much. The DOP method also showed change in the slope of the fitted curves for different OSNRs. To show this, we plotted the best fitted log_{10}(BER) versus DOP, which was averaged over seven channels for each of the three PMD distribution configurations in Fig. 9(d). It can be seen that while the slopes of the two configurations without power change had very similar slopes, with values of −0.085 for the distributed PMD and −0.088 for the PMD lumped at Tx, the lumped-at-Rx configuration with power change experienced a 15% slope change to −0.10. On the other hand, as shown in Fig. 6(d), the channel-averaged SOPL versus ∆ log_{10}(BER) is not dependent on OSNR and did not show a large curvature variation for the lumped-at-Rx configuration. This shows the robustness of the SOPL measurement approach to the amount of ASE present in the signal. The lack of dependence on OSNR further suggests that the SOPL is better for estimating PMD-induced penalty compared to DOP.
IV. Conclusion

We presented a stress study of PMD tolerance on a commercial 1600-km electronically predistorted 10-Gb/s fiber communication system using a spectral polarimeter. By inserting additional PMD and using intralink polarization scrambling, we sampled multiple configurations of the fiber parameter space, with an rms PMD of 40 ps. Simultaneous monitoring of pre-FEC BERs and the SOPL enabled us to correlate the error rates to the PMD-induced system degradation. Furthermore, we observed no correlation of SOPLs to power and OSNR fluctuations. We compared configurations with the PMD uniformly distributed across the link and lumped at the Tx or Rx end and showed that there was no significant difference between the three configurations for both BER and SOPL statistics, suggesting negligible interaction between PMD and nonlinearities in the system under test. We also compared PMD-penalty monitoring with an alternative method that uses DOP; it was demonstrated that string length has better correlation with PMD-originated BER and has the advantage of being insensitive to power change.

Acknowledgment

The authors would like to thank Avanex Corporation for donating the VIA and C. Antonelli for assisting with the calculations.

References


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