POLARIZATION DIVERSITY AND EQUALIZATION FOR PMD MITIGATION IN OPTICAL COMMUNICATION SYSTEMS

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ABSTRACT

We show that electrical domain (post-detection) approaches hold great promise for mitigating distortions such as polarization mode dispersion (PMD) in optical communication systems, when they are used by taking the physical characteristics of the distortion into account. We present a polarization diversity receiver for PMD mitigation and show its effectiveness by simulation results using accurate modeling of the PMD distortion. We also note that by incorporating electronic equalization into the diversity receiver structure further performance improvements can be achieved. We evaluate the system outage probability by calculating the power penalty due to PMD distortion and show its agreement with the simulation results.

1. INTRODUCTION

Polarization mode dispersion (PMD) is the primary barrier to achieving single-channel data rates at 40 Gbit/s and beyond in installed terrestrial fiber systems. By inducing polarization dependent propagation, PMD generates multiple images of light pulse carrying the information and leads to inter-symbol interference (ISI). A considerable effort has been devoted in recent years to mitigating the effects of PMD, based primarily on optical compensators (see, e.g., [1] and [2]). Optical compensation techniques are based on adaptive optics and they require the use of a polarization controller that can take hundreds of milliseconds to respond to system degradation. Moreover, optical compensators are expensive and bulky. Electrical domain approaches based on signal processing, on the other hand, offer great flexibility in design and can be integrated within the chip sets at the receiver, reducing bulkiness. Also, they can potentially operate after the optical signal has been partially demultiplexed so that electrical processing is done at a lower rate, hence substantially lowering the costs.

The work on electronic compensation in optical systems has mainly focused on the use of electronic equalizers with simple feedforward and decision feedback (DFE) structures (see, e.g., [3] – [6]) and these structures have been implemented and tested at 10 Gbit/s using integrated SiGe technology as analog equalizers [3] for PMD mitigation. However, optimization of the equalizer coefficients adaptively, even with the simple least mean squares (LMS) algorithm is still a challenging task at the high data rates at which optical systems operate. For example, in the adaptive equalizer of [6], only the center tap is adaptively computed while others are user-tuned.

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In this paper, we demonstrate that another electronic domain solution, the use of polarization diversity in the receiver, provides important performance gains by effectively mitigating the PMD distortion. We also show that by adding an equalizer to the diversity receiver, further gains are achieved, though marginal when compared to the improvement by the use of polarization diversity. Since all high-data-rate systems use direct detection, the polarization and phase information are lost during detection. Hence by using polarization diversity, we make efficient use of the available information for detection and provide better PMD mitigation than using an equalizer. Also, since the structure we introduce in this paper is based on fixed optics, it eliminates the need for bulky components such as polarization controllers as in [2].

First-order PMD distortion can be modeled as a stochastic linear multi-path type distortion with a short memory span whereas the higher-order distortions of PMD involve frequency variations of the polarization dispersion vector [7]. We present simulation results that show the effectiveness of the diversity receiver in reducing the system penalty due to PMD. In the simulations, we use the Manakov-PMD equation [8] to model the PMD effects, that include both the first and the higher-order effects and use accurate models [9] of the optical system components. We also evaluate the system outage probability by calculating the power penalty in the presence of first-order PMD distortion and show that the diversity receiver effectively reduces the power penalty induced by first-order PMD distortion while the equalizer reduces the power penalty due to higher-order PMD as well as the remaining part of the first-order distortion.

2. POLARIZATION MODE DISPERSION

Perturbations that cause loss of circular symmetry in the core and cladding of the fiber lead to birefringence and hence to PMD. Birefringence changes on a time scale that varies from milliseconds to hours [7]. Thus, within a time period of the order of milliseconds, the PMD-induced distortion can be considered to be a stationary process in a system whose bit rate is on the order of Gbit/s.

One of the important characteristics of optical fibers with PMD is that every frequency has two eigenstates, referred to as the principal states of polarization (PSP), which propagate through the fiber with different group velocity. The PSP pair have a time of flight difference that is defined as the differential group delay (DGD), τ. This difference in the arrival times of the two polarization states leads to pulse broadening. Light launched in one of the PSPs at the central frequency of the channel, on the other hand, does not experience first-order PMD distortion.

Given a fixed input polarization, the output polarization of the fiber undergoes a rate of rotation on the Poincaré sphere with respect to the frequency that can be characterized by [7]:

$$\frac{d\mathbf{s}}{d\omega} = \mathbf{\Omega} \times \mathbf{s}, \tag{1}$$

where $\mathbf{s}$ is the unit Stokes vector describing the output polarization state and $\mathbf{\Omega}$ is the polarization dispersion vector of the fiber. The magnitude of the polarization dispersion vector is equal to the DGD between the two PSP, $|\mathbf{\Omega}| = \tau$, while its direction determines the direction of the two orthogonal PSP, $\pm\mathbf{\Omega}/|\mathbf{\Omega}|$. The higher-order PMD distortion is due to the frequency dependence of the polarization dispersion vector $\mathbf{\Omega}$.

In high-data-rate optical systems, a photodetector, which can be modeled as a square-law detector, typically placed after an optical filter that provides a reduction of the noise, is used to convert the optical signal to electrical signal at the receiver. The effects of first-order PMD can be represented by the simple model

$$S_e(t) = \xi\left[\gamma S_o\left(t + \frac{\tau}{2}\right) + (1-\gamma) S_o\left(t - \frac{\tau}{2}\right)\right], \tag{2}$$

where $S_e(t)$ is the electrical signal at the photodetector output and $S_o(t)$ is the square of the optical field envelope. The coefficient ξ represents the conversion constant between the optical and electrical signals, γ, a random variable uniformly distributed in [0, 1], represents the distribution of power between the PSP pair, and τ is the DGD value that is Maxwellian distributed:

$$f_\tau(\tau) = \frac{32\tau^2}{\pi^2 \langle\tau\rangle^3} \exp\left(-4\tau^2/\pi\langle\tau\rangle^2\right), \tag{3}$$

where $\langle\tau\rangle$ is the mean DGD value.

The phase information as well as the polarization state information is not used in the decision as to whether the incoming bit is a mark (1) or a space (0). This suggests important gains through the use of polarization diversity at the receiver as we show next.

3. POLARIZATION DIVERSITY RECEIVER

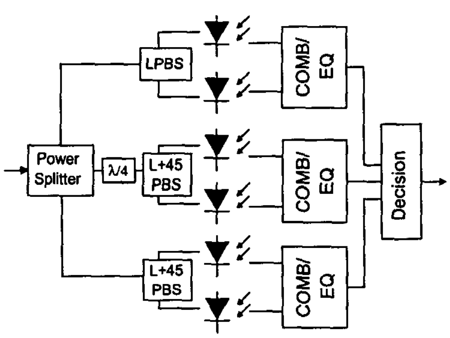

Fig. 1. Polarization Diversity Receiver

Figure 1 shows the diversity receiver that we introduce. The incoming signal is equally split into three pairs of orthogonal polarization that are detected by independent photodetectors. The advantage of using pairs of orthogonal polarizations is to allow the detection of the total signal power in such a way that the power margin can be increased while maintaining the original noise distribution in the system. In the first branch of the proposed diversity receiver, a linear polarization beam splitter (LPBS) is used to split the signal between vertical and horizontal polarizations. In the second branch, a quarter-wave plate ($\lambda/4$) converts the signal from circular to linear polarization before the polarization beam splitter (PBS), that is rotated by 45 degrees with respect to the first PBS, which splits the signal into right- and left-circular polarizations. In the third branch, the PBS splits the signal into two diagonal (45° and −45°) polarizations. The PBS consist of two ideal linear polarizers oriented orthogonal to each other and the transmission through a perfect polarizer can be characterized by [7]:

$$T(\omega) = \frac{1}{2}\left(1 + \hat{\mathbf{s}}(\omega) \cdot \hat{\mathbf{p}}\right). \tag{4}$$

where $\hat{\mathbf{s}}(\omega)$ is the polarization of light incident on the polarizer and $\hat{\mathbf{p}}$ is a unit vector denoting the "high-pass" state of the polarizer. The combiner/equalizer block combines the pairs of signals synchronized by an electrical delay. Discrete samples are obtained by a clock recovery subsystem and a decision circuit (CLK/DEC block in the figures). Finally, the decision module selects the branch that has the maximum power margin.

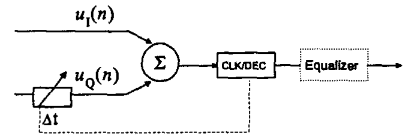

Fig. 2. The Combiner/Equalizer Block (can be implemented with or without an equalizer)

For combining the pairs of orthogonal polarizations in each of the three branches, we study two implementations: a simple combiner and a combiner followed by an equalizer as shown in Fig. 2. The equalizer is realized as a transversal filter with a symmetric structure such that the input vector is defined as $[u(n + (M-1)/2), \ldots,\ u(n),\ u(n-1), \ldots,\ u(n-(M-1)/2)]$ assuming that the order of the equalizer M is odd and the current sample is $u(n)$. The noncausal structure helps eliminate the ISI introduced by both the preceding and the succeeding pulses and a small order M is typically sufficient as the ISI induced by PMD distortion usually only extends to the closest neighbor pulses. A DFE with possibly a lower order could have been effectively used as well, however the transversal structure is easier to implement than a decision feedback at the Gbit/s rates and they provide similar performance in PMD mitigation when the transversal filter is implemented with a symmetric structure.

We use mean square error (MSE) optimization for calculating the filter coefficients and assume discrete implementation of the equalizer so that the MSE solution directly maximizes the mean eye opening at the sampling instant as opposed to continuous-time minimum MSE equalization. In the case of continuous-time equalization, MSE minimization leads to maximization of the eye opening within the pulse period and hence is nonoptimal for the task [6]. To evaluate the performance gain by an equalizer when added to the diversity reciver, we directly use the Wiener estimates within appropriately selected time windows. The LMS algorithm can be used to adaptively approximate the Wiener solution as implemented in [3] for PMD mitigation (without diversity). Also, since the optical systems typically operate at very low bit error rates, we use decision-directed equalization in the implementation.

4. PERFORMANCE EVALUATION - CALCULATION OF PMD OUTAGE

Even though the polarization dispersion vector $\boldsymbol{\Omega}$ is a random quantity that is frequency dependent, it has a correlation bandwidth in which both the DGD and the PSP vary very little as a function of frequency. This correlation bandwidth is approximately $\Delta\nu \approx 0.5/\langle\tau\rangle$ [7], where $\langle\tau\rangle$ is the average DGD. For a DGD value of $\langle\tau\rangle = 25$ ps, the frequency bandwidth approximately equals 20 GHz. The PMD-induced penalty will thus be highly correlated with the DGD at the central frequency of the channel in a 10 Gbit/s nonreturn-to-zero (NRZ) systems. Consequently, for systems with a DGD value in this range, the system penalty is dominated by first-order PMD, and this is a typical range for practical systems. In what follows, we show that we can numerically evaluate the PMD outage due to first-order PMD that we described in (2).

In optical systems, outage probability is the parameter used to evaluate the PMD sensitivity. Designers specify a power margin for the PMD (typically 2 or 3 dB), and they want to ensure that the probability that that the actual power penalty exceeds this power margin is very low. This probability is referred to as the outage probability. The power margin is the difference between the the minimum value for a mark (bit 1) and the maximum value for a space (bit 0) of the electrical signal at the sampling instant, $I_1 - I_0$. The isolated marks and spaces are the patterns that suffer the largest amount of ISI due to PMD.

The power penalty (y) is defined as:

$$y = \frac{(I_1 - I_0)_{\text{w/o PMD}}}{(I_1 - I_0)_{\text{with PMD}}}. \qquad (5)$$

As the penalty is expressed in dB, the PMD outage of β dB in $S_o(t)$ is given by:

$$\text{Prob}\,(y \geq \beta) = \text{Prob}\left(I_1 - I_0 \leq 10^{-\beta/10}\right). \qquad (6)$$

Since τ and γ are Maxwellian and uniform distributed, respectively, and are independent of each other the probability that the power penalty is greater than β is given by:

$$\Pr(y \geq \beta) = \int_0^1 \int_{\tau_{\min}(\gamma)}^{\infty} \frac{32\tau^2}{\pi^2 \langle\tau\rangle^3} \exp\left(-4\tau^2/\pi\,\langle\tau\rangle^2\right) d\tau d\gamma, \qquad (7)$$

where $\tau_{\min}(\gamma)$ is the DGD threshold and $\langle\tau\rangle$ is average DGD, the PMD value. The main difficulty in analytical evaluation of this integration is that the limits of the integrals are inter-dependent, such that $\tau_{\min}(\gamma)$, the DGD threshold above which the specified penalty β occurs, is a function of γ. For example, if $\gamma = 0$ or $\gamma = 1$, the signal propagates in only one of the PSP and hence does not suffer first-order PMD distortion. On the other hand, if $\gamma = 0.5$, equal contributions from the PSP pair with a time delay are received at the photodetector hence producing the worst first-order PMD distortion, and consequently the largest power penalty.

To observe the dependence of $\tau_{\min}(\gamma)$ on γ, consider the case where $\gamma = 0.5$. Let $\xi = 1$ and the optical pulse shape be a raised cosine:

$$S_o(t) = \frac{1}{2}\left[1 + \cos\left(\frac{\pi t}{T}\right)\right], t \in \left[-\frac{T}{2}, \frac{T}{2}\right], \qquad (8)$$

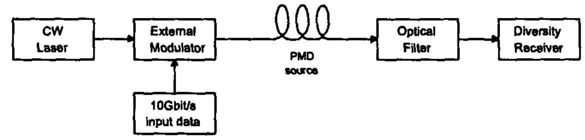

Fig. 3. Optical Transmission System

where T is the bit period. Then

$$I_1 = S_e(t) = \frac{1}{2}S_o\left(t + \frac{T}{2}\right) + \frac{1}{2}S_o\left(t - \frac{T}{2}\right). \qquad (9)$$

For $\gamma = 0.5$ the sampling point at center of the bit period will be at $t = 0$, and given that $S_o(t)$ is symmetric we obtain:

$$I_1 = S_e(0) = S_o\left(\frac{T}{2}\right). \qquad (10)$$

For DGD values $\tau < T/2$ (the DGD range we primarily consider), I_0 is equal to zero and the power margin becomes equal to I_1 and using (6) and (8) yields the DGD threshold:

$$\tau \geq \frac{2T}{\pi}\cos^{-1}\left(-1 + 2\cdot 10^{-\beta/10}\right) = \tau_{\min}(0.5). \qquad (11)$$

Hence, we evaluate the integral in (7) numerically and use the result to study the performance of the diversity receiver in reducing first and higher-order PMD distortion.

5. SIMULATION RESULTS

We test the diversity receiver in the transmission simulation setup shown in Fig. 3, which enables a well defined PMD distortion to be induced into the 10Gbit/s test signal in a practical optical transmission system, and the measurement of the power penalty. The continuous wave light from a laser diode is externally modulated by an intensity modulator which is driven by the 10Gbit/s input data with string length of 256 pulses. The pulses generated by the modulator are standard NRZ with raise time of 30 ps, optical carrier wavelength of 1532nm and peak power of 1 mW. We use an optical fiber as the source of PMD and assume that the fiber passes ergodically through all possible polarization states with the same PMD. Thus, we analyze ensembles of fibers with the same PMD in order to compute the outage probability for each case. We use 10,000 fiber realizations each 100 km in length and model the fiber using 80 sections of birefringent elements with the coarse step method [8], which reproduces first and higher-order PMD distortions. As the optical filter we use a Gaussian bandpass filter with 60 GHz of full width of half maximum and as an electrical filter a lowpass Bessel filter of 5-th order that is placed after the photodetector in the diversity receiver. The filters are used primarily for noise suppression. When a linear equalizer is added to the combiner block (Fig. 2), the order is chosen as seven ($M = 7$).

In order to study the probability that the system penalty exceeds a certain margin, typically 2 or 3 dB, we use importance sampling applied to PMD as in [10]. The importance sampling technique allows us to accurately calculate the outage probability due to PMD at realistic values of 10^{-6} with a relatively small number of Monte Carlo simulations by biasing the probability density function (pdf) of the DGD in such a way as to cause the large-DGD events to occur more frequently.

In Figures 4 and 5, we show the complement of the cumulative distribution function (cdfc) of the power penalty β caused by PMD in an NRZ system with average DGD values of $\langle\tau\rangle = 20$ ps and $\langle\Delta\tau\rangle = 25$ ps, respectively. The cdfc gives the probability of having a power penalty greater than a given amount. These figures show the cdfc of the power penalty caused by PMD using direct and diversity detection with fixed optics.

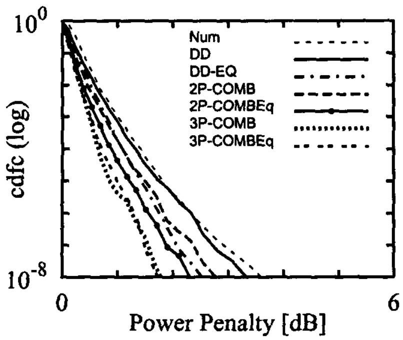

Fig. 4. The cdfc of the power penalty caused by PMD for an average DGD value $\langle\tau\rangle = 20$ ps. The curves show results with (i) Numerical results with first-order PMD alone; (ii) DD: direct detection without equalization; (iii) DD-EQ: direct detection with equalization (no diversity); (iv) 2P-COMB: two pairs of orthogonal polarizations with a simple combiner; (v) 2P-COMBEq: two pairs of orthogonal polarizations with a simple combiner and an equalizer; (vi) 3P-COMB: three pairs of orthogonal polarizations with a simple combiner; (vii) 3P-COMBEq: three pairs of orthogonal polarizations with a simple combiner and an equalizer.

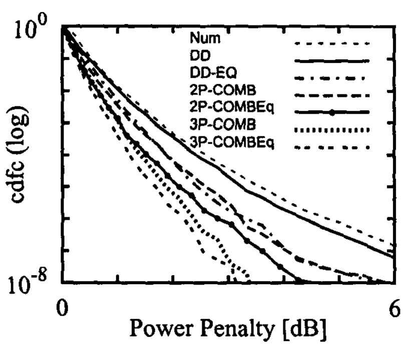

Fig. 5. Same group of comparisons as in Figure 4 for $\langle\tau\rangle = 25$ ps.

We first note that for high average DGD values, such as $\langle\tau\rangle = 25$ ps, our proposed receiver presents a remarkable improvement in decreasing the outage probability when compared to the case with direct detection. The receiver configuration for three pairs of orthogonal polarizations realized with a simple combiner provides a reduction of 2 dB on the penalty that defines an outage probability of 10^{-6} (Fig. 5), as compared to the non-equalized case with direct detection (with no diversity). The receiver configuration implemented with two pairs of orthogonal polarizations (vertical/horizontal and right/left-circular) and a simple combiner performs about the same as an equalized case with no diversity. This configuration, however, cannot approach the performance of the receiver with three pairs of orthogonal polarizations. The detection of three pairs of orthogonal polarizations equally spaced over the Poincaré sphere allows the receiver to obtain at least one pair of orthogonal polarizations of the signal with a reduced PMD distortion. A receiver with one or two pairs of orthogonal polarization, on the other hand, cannot always perform better than direct detection because it is possible for the principal states of polarization (PSP) of the fiber to be orthogonal to the polarizations detected. Hence, the operating principle of the polarization diversity receiver is to detect the pair of orthogonal polarizations that is closest to the PSP.

We note that the equalization leads to little additional penalty reduction when added to the diversity receiver with three orthogonal polarizations. It does, however, lead to visible additional penalty reduction when added to the direct detection receiver. Intuitively, the diversity structure mitigates the effects of first-order distortion so that what is left for the equalizer is primarily the ISI due to higher-order distortions and residual first-order distortion left by the diversity structure, which is small. When the average DGD $\langle\tau\rangle = 20$ ps, Fig. 4 shows that with this low a value of the average DGD, no visible improvement is achieved with an equalizer. In this case, the distortions are almost entirely due to first-order PMD distortions and are effectively mitigated by the diversity structure. To observe the dominance of first-order PMD distortion, note the closeness of the two curves in the figures: the decision directed curves that models all orders of PMD and the numerically evaluated curves that consider only first-order PMD.

6. REFERENCES

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