A Novel Polarization Diversity Receiver for PMD Mitigation

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***Abstract*—In this letter, we present a novel polarization diversity receiver for mitigating polarization-mode dispersion (PMD). We show that with simple fixed optics and electronics we can significantly decrease the outage probability due to PMD and can achieve better performance than an electronic equalization solution using no diversity. By incorporating equalization into the diversity receiver structure, further performance improvements can be achieved and the intersymbol interference due to higher order PMD distortions can be reduced. We demonstrate the performance advantages of the proposed diversity receiver using importance sampling to accurately calculate the outage probability due to PMD.**

***Index Terms*—Diversity methods, equalizers, intersymbol interference, optical communications, optical fiber polarization, PMD mitigation.**

I. INTRODUCTION

IN HIGH-SPEED optical communication systems at data rates of 10 Gb/s and beyond, signal distortion caused by polarization-mode dispersion (PMD) is a significant barrier to the transmission bit rate $\times$ distance product. A considerable effort has been devoted in recent years to mitigate the effects of PMD, based on optical, electrical, and optoelectrical PMD compensators [1]–[5].

Among the PMD compensation techniques, electrical domain (post-detection) approaches are particularly attractive because of their potential for compact and cost-effective implementation in the chip sets at the receiver. Electronic equalizers using simple feedforward and decision feedback structures have been proposed for mitigating intersymbol interference (ISI) in optical communications [1], and have been recently implemented and tested at 10 Gb/s using integrated SiGe technology as analog equalizers [2] for PMD mitigation. However, it is noted that they do not deliver the performance gains typically expected and the optimization of filter coefficients adaptively, even with the simple least mean squares (LMS) algorithm [7] is still a challenging task at the high data rates at which optical systems operate.

Since all high data rate systems use direct detection, the polarization phase information is lost during detection and diversity can provide additional advantages for PMD mitigation by making more efficient use of the available information. A technique based on adaptive optics and diversity detection is described in [3], where a polarization beam splitter (PBS) is used to split the signal into two orthogonal polarizations that are recombined in the electrical domain using an electrical delay line and a combiner. Another diversity detection scheme that is based on fixed optics is presented in [4], in which three polarizations are extracted from the optical signal to be recombined in the electrical domain. In this scheme the three receiver photodetector signals are adaptively weighted by different weighting factors and then superimposed.

In this contribution, we present a novel polarization diversity receiver and show that by using simple fixed optics and electronics we can obtain significantly better performance than is possible with the use of an equalizer (with no diversity) that requires optimization of the filter taps by some means. We also show that by incorporating electronic equalization into the diversity receiver structure, the ISI due to higher order PMD distortions can also be reduced. However, the performance improvement with the addition of an equalizer is not as significant since first-order PMD distortion usually dominates and is effectively mitigated by the diversity structure.

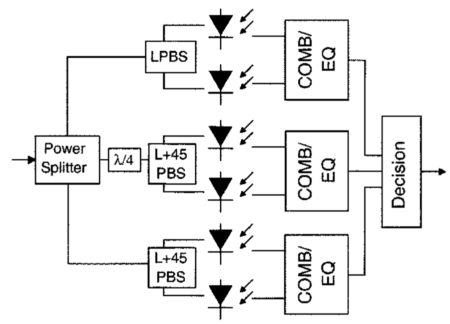

Fig. 1. Polarization diversity receiver.

II. POLARIZATION DIVERSITY RECEIVER STRUCTURE

The block diagram of Fig. 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 amplitude margin can be increased, while maintaining the original noise distribution in the system, in contrast to a structure that uses single polarizations [4], and hence, has higher sensitivity to noise. In the first branch of the proposed diversity receiver, a linear PBS (LPBS) is used to split

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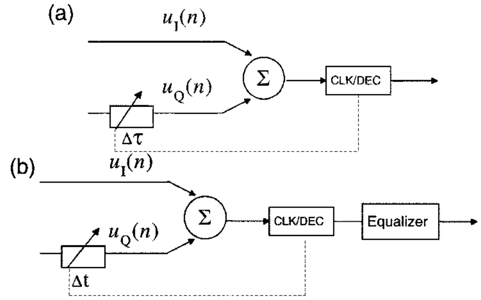

Fig. 2. Two implementations of combiner/equalizer (COMB/EQ) block. (a) Simple combiner. (b) Simple combiner and equalizer.

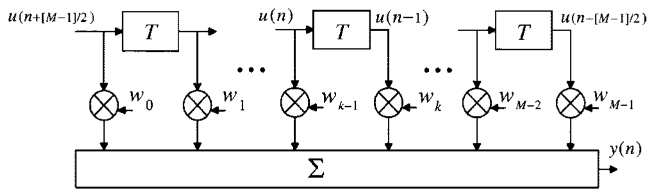

Fig. 3. Transversal filter.

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 PBS, that is rotated by 45° with respect to the first PBS, which splits the signal into right- and left-circular polarizations. In the third branch, a PBS splits the signal into two diagonal (45° and $-45°$) polarizations. 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 amplitude margin.

We examine a combiner/equalizer block both with and without equalization. These structures are shown in Fig. 2. The first structure is a simple combiner for each pair of orthogonal polarizations. It utilizes only polarization diversity to reduce the ISI. The second structure adds to the combiner a standard electrical equalizer whose coefficients are computed by mean square error (MSE) minimization [7]. The structures shown in Fig. 2 are the ones that exhibit the best tradeoff in robustness in the presence of PMD-induced distortion and implementation complexity among a number of different choices that we have investigated. In [5], we introduce and study the performance of a complex equalizer with a similar diversity structure where the pairs of polarizations are used to define the inphase and quadrature parts of the complex signal. The structures that we introduce in this paper exhibit comparable performance to that of the complex equalizer with diversity [5] with a significant reduction in complexity.

The linear equalizer used in this letter is realized as a transversal filter and is sampled at bit period, as shown in Fig. 3. We use symmetric equalization, i.e., each bit is equalized using the previous $(M-1)/2$ and the future $(M-1)/2$ bits, assuming that M is odd. In this case, the middle sample is the current sample. We use symmetric equalization and a relatively small number of taps because the ISI induced by PMD distortion usually only extends to the closest neighbor pulses.

Work to date on PMD compensators based on adaptive optics, such as [3], requires the use of a polarization controller (PC). However, PCs that are fast enough to respond to system degration are expensive and bulky. The receiver that we introduce, on the other hand, is based on fixed optics and electronic processing, and it thus offers the prospect of potentially resolving many of the problems faced by optical compensators.

III. Performance Evaluation

Outage probability is a critical parameter in evaluating the performance of a PMD mitigation scheme, and is hence, the criterion that we utilize. Designers specify a power margin for the PMD, and they want to ensure that the probability that the power penalty due to PMD exceeds this margin, i.e., the outage probability, is very low. 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 [6]. The power penalty is defined as the ratio between the power margin without PMD distortion (back-to-back) and the PMD distorted power margin.

It is not practical to use standard Monte Carlo methods to calculate the outage probability of optical transmission systems due to PMD to ensure that it is 10^{-6} or less because it would require using on the order of 10^8 realizations to do so. 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. We assume that the fiber passes ergodically through all possible polarization states with the same PMD. We model the fiber using 80 sections of birefringent elements with the coarse step method, which reproduces first and higher order PMD distortions.

In order to evaluate the optimal performance of the linear equalizer with seven taps ($M = 7$), we calculate the coefficients of the filter using the Wiener solution [7], that minimizes the MSE. The LMS algorithm can be used to adaptively compute (approximate) the Wiener solution for PMD mitigation. A fractionally spaced equalizer can also be used to improve the performance, however, in our implementation, we use a standard equalizer sampled at the bit period considering the limitations of implementation with the current integrated circuit technology.

IV. Simulation Results

Figs. 4–6 show the complement of the cumulative distribution function (cdfc) of the power penalty caused by PMD in a 10 -Gb/s nonreturn-to-zero (NRZ) system with average differential group delay (DGD) values of $\langle\Delta\tau\rangle = 20$ ps, $\langle\Delta\tau\rangle = 25$ ps, $\langle\Delta\tau\rangle = 30$ 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. In the simulations that we present, we assume the noise free case and focus on the PMD-induced penalty.

We first note that for high average DGD values, such as $\langle\Delta\tau\rangle$ equal to 25 and 30 ps, our proposed receiver scheme presents a remarkable improvement in decreasing the outage probability when compared to the case with direct detection. The diversity receiver provides better performance, even when compared to

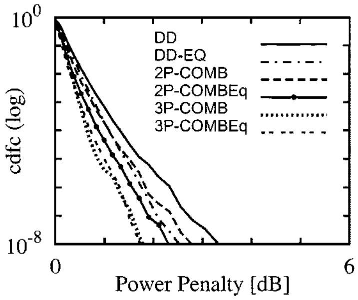

Fig. 4. The cdfc of the power penalty caused by PMD in an NRZ system with average DGD $\langle \Delta\tau \rangle = 20$ ps. The curves show results with i) DD: direct detection without equalization; ii) DD-EQ: direct detection with equalization (no diversity); iii) 2P-COMB: two pairs of orthogonal polarizations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

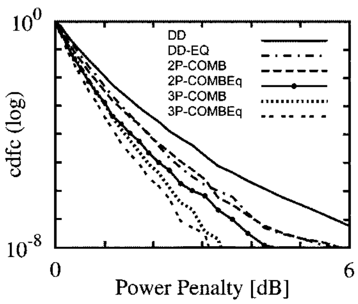

Fig. 5. Same group of comparisons as in Fig. 4 for $\langle \Delta\tau \rangle = 25$ ps.

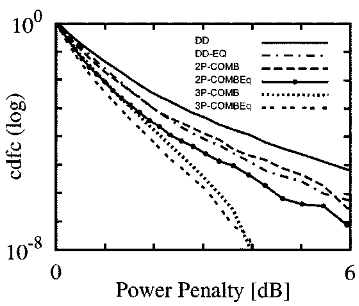

Fig. 6. Same group of comparisons as in Fig. 4 for $\langle \Delta\tau \rangle = 30$ ps.

the case where direct detection is followed by equalization. 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 nonequalized case with direct detection with no diversity. Also, as the average DGD values increase (Figs. 5 and 6), the advantage of the diversity receiver with three pairs of orthogonal polarizations becomes more pronounced.

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 operating principle of the polarization diversity receiver is to detect the pair of orthogonal polarizations that is closest to the principal states of polarization (PSP) of the fiber. 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. By contrast, a receiver with one or two pairs of orthogonal polarization cannot always perform better than direct detection because it is possible for the PSP of the fiber to split evenly between the polarizations detected.

We note that the equalization leads to little additional penalty reduction when added to the diversity receiver with three orthogonal polarizations. By contrast, it does 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 $\langle \Delta\tau \rangle = 20$ 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. Also, an equalizer requires optimization of the filter coefficients, either user tuned [2] or adaptively computed as in [5], implying a substantial increase in the receiver complexity. On the other hand, a diversity receiver with the simple combiner does not require any coefficient optimization and can be realized with the current technology at 10-Gb/s speeds and beyond. Although it does require multiple photodetectors for each wavelength channel, it is possible in principle to reduce costs by using the same clock recovery circuit in a round-robin fashion with each of the photodetectors.

V. Conclusion

We introduced a novel diversity receiver structure with three fixed pairs of orthogonal polarization symmetrically distributed on the Poincaré sphere. We then applied importance sampling to quantify the power penalty due to PMD. Our results showed that the diversity receiver achieves a significantly larger reduction of the power penalty than can be achieved using an electronic minimum MSE equalizer alone. We also showed that combining the equalizer with the diversity receiver offers little additional improvement.

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