Electronic Equalization of Polarization Mode Dispersion in Coherent POL-MUX QPSK Systems

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Abstract *We present a comparison of adaptive electronic PMD equalizers for coherent phase - and polarization-diversity QPSK receivers using the multicanonical Monte Carlo method. A 5-tap equalizer using the CMA sufficiently reduces the outage probability below 10^{-5}.*

Introduction

Coherent receivers used for the detection of polarization-multiplexed (POL - MUX), quadrature phase shift keying (QPSK) optical signals offer the capability of unlimited chromatic dispersion and polarization mode dispersion (PMD) compensation using electronic equalization. Recent experiments have demonstrated almost unlimited compensation of 1st order PMD, provided electronic equalizers have enough filter taps[1]. All-order PMD, created in a recirculating loop containing a 1st order PMD source and a loop-synchronous scrambler, produces penalties below the FEC threshold, in a single channel system[2]. Measurements with extremely large, *instantaneous* differential group delay (DGD) indicate that penalties can always be kept below 3 dB[3]. However, to the best of our knowledge, no theoretical comparison of the performance of adaptive electronic PMD equalizers for coherent POL-MUX QPSK optical communications systems exists in literature.

In this paper, we estimate the robustness of electronically-equalized, coherent POL-MUX QPSK optical communications systems with respect to all-order PMD. We use a PMD emulator (PMDE), comprised of randomly-oriented birefringent sections, and apply the Multicanonical Monte Carlo method (MMC)[4] to efficiently calculate low values of the outage probability. In previous theoretical evaluations of PMD statistics, the DGD[4] was used as the control parameter of the MMC algorithm. Here, by choosing the control parameter as the OSNR penalty, we generate low values of outage probability in a computationally-efficient manner. The OSNR penalty is defined as the difference in the OSNR required to achieve a bit error probability equal to 10^{-9} between the back-to-back and the PMD-distorted case. We adopt Poole's[5] original definition for the outage probability. as the cumulative probability that the OSNR penalty exceeds a specified threshold. Using a threshold of 1 dB[5], a 5-tap equalizer is found to produce an outage probability lower than 10^{-5}, for mean DGD half of the symbol period.

MMC method

The MMC method is used to iteratively compute the probability density function (pdf) of the outage probability, with little, if any, a priori knowledge of how to bias the input random variables, in order to generate more frequently rare events[4]. Here, as input random variables we choose the parameters of the N birefringent sections of the PMDE, i.e, the azimuth and ellipticity $\{\alpha_i,\varepsilon_i\}$ of their principal axes, and the differential group delay $\{\Delta\tau_i\}$ (DGD), where $i=1,2,....,N$. Assuming appropriate pdfs for the N triplets $\{\alpha_i,\varepsilon_i,\Delta\tau_i\}$[4], the corresponding PMD vectors are uniformly distributed over a Poincaré sphere with Gaussian length.

The guiding principle behind the MMC method is the following: OSNR penalties greater than a given threshold, and the corresponding PMD outages, occur for certain rare combinations of the magnitude of local birefringence and orientation of principal axes along the PMDE. These rare combinations are artificially made to occur more frequently, compared to a simple Monte Carlo, the execution time required for the evaluation of the performance of a POL-MUX QPSK system using electronic equalization is drastically reduced.

System Model

The block diagram of the system under study is shown in Fig. 1. The output of a CW laser (Tx laser), having 45° linear output polarization, is divided, using a polarization beam splitter (PBS) into equal x, y polarization components. Each polarization component is QPSK modulated using a dedicated quadrature modulator (QM). The pseudorandom data sequences at the input of the quadrature modulators

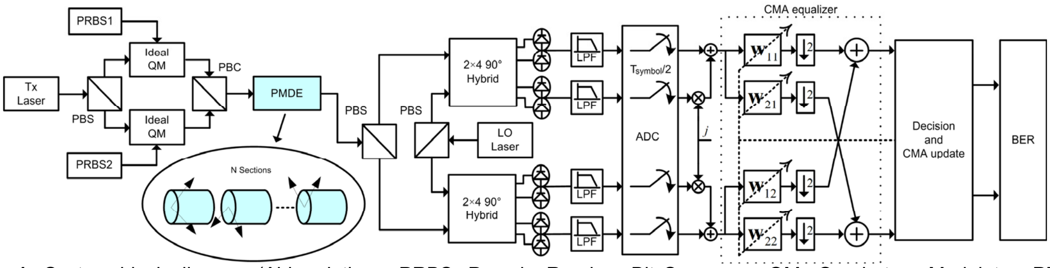

Fig. 1: System block diagram (Abbreviations: PRBS: Pseudo-Random Bit Sequence, QM: Quadrature Modulator, PBS: Polarization Beam Splitter, PBC: Polarization Beam Combiner, PMDE: PMD Emulator, LO: Local oscillator, LPF: Low Pass Filter, T_{symbol}: Symbol period, **w**: FIR filters' taps, CMA: Constant Modulus Algorithm).

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are appropriately selected so that the generated QPSK symbols are De Bruijn sequences, in order to take into account all possible combinations of 5 consecutive symbols causing PMD-related inter-symbol interference (ISI). Ideal, non-return-to-zero (NRZ) QPSK pulses are assumed. Then, the two polarization components x, y are recombined prior to transmission.

A coherent, homodyne, polarization- and phase-diversity receiver is used, consisting of 2×4 90° optical hybrids, followed by balanced detectors [6]. The photocurrents are resampled to twice the baud rate and fed into an adaptive electronic equalizer using the constant modulus algorithm (CMA). The latter performs polarization demultiplexing and PMD equalization[7]. It is assisted by a phase-error estimator, which is able to remove any small residual constellation rotations[7]. The average probability of error is estimated using a semi-analytical method[8].

In our simulations, we assume a homodyne system with symbol rate R_s per polarization, and 4th order Bessel low pass filters at the receiver, with $0.8R_s$ 3-dB bandwidth. The OSNR penalty is calculated at bit-error probability 10^{-9}, using, as a reference, a back-to-back system with a one-tap electronic demultiplexer[9].

The PMDE consists of 30 birefringent sections. In each MMC iteration, 1000 implementations of the PMDE are generated, and the outage probability is evaluated at the last iteration and for OSNR penalties larger than a 1 dB threshold.

Results and Discussion

We present here indicative simulation results for the following cases: (i) without electronic equalization (a polarization demultiplexer with one symbol-spaced tap/filter[9]); and (ii) with CMA equalizers with two and five $T_S/2$-spaced taps per filter (where T_S is the symbol period). A qualitative comparison of the performance of a 5-tap adaptive electrical CMA equalizer with respect to the uncompensated case, for indicative normalized DGD instantaneous values, is shown in Fig. 2.

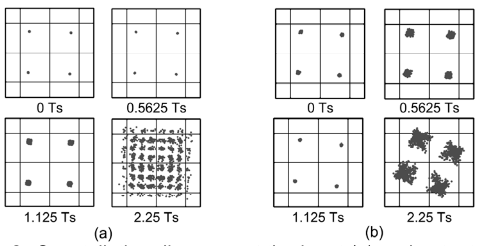

Fig. 2: Constellation diagrams at the input (a) and output (b) of the 5-tap CMA equalizer for normalized instantaneous DGD $0T_S$, $0.5625T_S$, $1.125T_S$ and $2.25T_S$.

The CMA equalizer reduces significantly higher-order PMD, as it efficiently opens the constellation diagrams, even for instantaneous DGD values equal to $2.25T_S$. Also, we observe that, at the output of the 5-tap CMA equalizer, the constellation diagram is arbitrarily rotated, but this rotation is eliminated after differential decoding.

In Fig. 3, the outage probability is plotted as a function of the mean DGD, normalized to the symbol period, using both the conventional MC method (dotted, squared and dashed-dotted lines) and the MMC method (dots and circles) method, respectively.

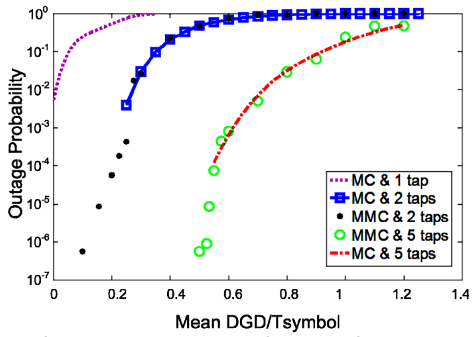

Fig. 3: Outage probability as a function of the normalized mean DGD, evaluated: (i) using the conventional MC method with 1-tap per filter polarization demultiplexing (dotted line), and with CMA equalization (squared lines for 2 taps and dashed-dotted line for 5 taps); (ii) using the MMC method, for a 2-tap per filter CMA equalizer (dots) and for its 5-tap per filter counterpart (circles), respectively.

The 5-tap CMA equalizer shows superior performance for higher-order PMD. The mean DGD is allowed to increase from $0.22T_S$, for the 2-taps per filter CMA equalizer, to $0.58T_S$, for the 5-tap per filter CMA equalizer, at an outage probability of 10^{-5}. It is worth noting that the filter length requirement for electronic equalizers provided by the first-order PMD study[1] are optimistic, compared to the present study. The reason for this discrepancy is the following: in uncompensated systems, the outage probability is dominated by first-order PMD, whereas in compensated systems, higher-order PMD must be taken into account.

Conclusions

We evaluated, for the first time, the impact of PMD on the performance of a coherent POL-MUX QPSK system using the outage probability as a performance criterion. The use of the MMC method allows for effectively generating extremely rare cases of PMD outages. A 5-tap per filter electronic CMA equalizer can increase the tolerable mean DGD per symbol period to 58%, at an outage probability of 10^{-5}.

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