

Training Symbol Based Channel Estimation for Ultrafast Polarization Demultiplexing in Coherent Single-Carrier Transmission Systems with M -QAM Constellations

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Abstract We propose a training symbol based algorithm that estimates the Jones channel matrix whose entries are used as the initial center taps of a decision-directed butterfly equalizer. With fewer than 40 training symbols, we experimentally demonstrate ultrafast polarization demultiplexing for 112 Gbps PDM-QPSK and 224 Gbps PDM-16QAM systems.

Introduction

Polarization division multiplexing (PDM) is an efficient way to double spectral efficiency in optical transport systems¹. Along the fiber, the signal suffers from linear impairments such as chromatic dispersion (CD), random polarization rotation and polarization mode dispersion (PMD)². Using a polarization-diversity coherent receiver, CD is first compensated by a static frequency domain equalizer (FDE)². Then, the two polarizations are reconstructed by a butterfly equalizer that mitigates polarization crosstalk and inter-symbol interference (ISI) due to PMD, filtering effects, and residual CD². Several algorithms have been used for adapting the taps of the butterfly equalizer. Data-aided schemes are widely used where training symbols (TS) are sent and used at the receiver for tap adaptation using the least mean square (LMS) algorithm³. Such schemes reduce throughput and therefore, blind techniques such as the constant modulus algorithm (CMA) are preferred. CMA is widely used for quadrature phase shift keying (QPSK)². Even for high order QAMs having non constant modulus, e.g. 16QAM, CMA still achieves reasonable pre-convergence after which adaptation is switched to decision-directed LMS (DD-LMS) for steady-state operation⁴. However, CMA may converge slowly depending on the state of polarization (SOP) of received light and has a singularity problem where both outputs converge to the same polarization⁵.

In this paper, knowing that modern fibers have very small PMD parameter (< 0.1 ps/km^{1/2})⁶, we propose a training symbol based algorithm that estimates the 2x2 Jones matrix assuming initially the channel is flat in the frequency domain. The estimated matrix entries are then used to set the initial center taps of a butterfly equalizer. As polarization crosstalk is mitigated, initial constellations are reasonably compact such that decision-directed adaptation can be started after as few as 40 training symbols for

estimation, thus achieving ultrafast polarization demultiplexing. Our algorithm is experimentally tested on both 112 Gbps PDM-QPSK and 224 Gbps PDM-16QAM systems and compared with TS-LMS and CMA for initial convergence.

Principle of proposed algorithm

Assuming CD is first compensated and the channel is flat in frequency, a fiber channel can be modeled as a unitary 2x2 Jones matrix \mathbf{R}^2

$$\mathbf{R} = \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix} \quad (1)$$

$$a = e^{j\delta} \cos\theta, \quad b = e^{j\varphi} \sin\theta$$

where 2θ and φ are the azimuth and elevation rotation angles, respectively, whereas 2δ is a differential phase between the two polarizations. Assuming Nyquist pulses, the received signal

$\mathbf{S}_{rx}[n] = [s_{rx}^x[n] \ s_{rx}^y[n]]^T$ can be expressed as

$$\mathbf{S}_{rx}[n] = e^{j\psi[n]} \mathbf{R} \mathbf{S}_{tx}[n] = e^{j\psi[n]} \begin{bmatrix} a s_{tx}^x[n] + b s_{tx}^y[n] \\ -b^* s_{tx}^x[n] + a^* s_{tx}^y[n] \end{bmatrix} \quad (2)$$

where $\mathbf{S}_{tx}[n] = [s_{tx}^x[n] \ s_{tx}^y[n]]^T$ is the transmitted signal and $\psi[n]$ is the instantaneous phase of the n^{th} symbol originating from laser phase noise $\psi_{pn}[n]$ and frequency offset Δf as follows

$$\psi[n] = 2\pi\Delta f T + \psi_{pn}[n]$$

The principle of the proposed algorithm is to send short special training symbols on X and Y polarizations and use the received data to estimate \mathbf{R} regardless of laser phase noise and frequency offset. Basically, we send N training symbols $\mathbf{T}_{tx}[k]$, where $k \in [0, N-1]$, designed such that: $\mathbf{T}_{tx}[k] = c e^{j\vartheta} [1 \ 1]^T$ and $\mathbf{T}_{tx}[k+1] = c e^{j\vartheta} [1 \ -1]^T$, where $\vartheta \in \{\pm\pi/4, \pm 3\pi/4\}$ and c is a normalization constant that is chosen depending on the modulation format such that we always send one of the four constellation corner symbols on the X and Y polarizations for the training period where the phase shift

between two polarization multiplexed training symbols alternates between 0 and π . Using (2), we can write the received training symbols as

$$\mathbf{T}_{rx}[k] = ce^{j(\theta+\psi[k])} \begin{bmatrix} a+b \\ -b^*+a^* \end{bmatrix}, \quad \mathbf{T}_{rx}[k+1] = ce^{j(\theta+\psi[k+1])} \begin{bmatrix} a-b \\ -b^*-a^* \end{bmatrix}$$

Knowing that $\psi[k] \approx \psi[k+1]$ as it is a slower process compared to the baud rate and that \mathbf{R} is unitary, if we normalize the received training symbols to unit envelope, we can get

$$|a| \approx \sqrt{0.5 \left(1 + \frac{1}{N} \operatorname{Re} \left\{ \sum_{i=0}^{N/2-1} \begin{pmatrix} T_{rx}^x[2i] T_{rx}^{x*}[2i+1] - \dots \\ T_{rx}^y[2i] T_{rx}^{y*}[2i+1] \end{pmatrix} \right\} \right)} \quad (3)$$

$$|b| \approx \sqrt{1 - |a|^2} \quad (4)$$

$$\arg\{a\} + \arg\{b\} = \arg \left\{ - \sum_{i=0}^{N/2-1} \begin{pmatrix} T_{rx}^x[2i] T_{rx}^{y*}[2i+1] + \dots \\ T_{rx}^y[2i] T_{rx}^{x*}[2i+1] \end{pmatrix} \right\} \quad (5)$$

Then, if the inverse of the matrix \mathbf{R}_1 given by

$$\mathbf{R}_1 = \begin{bmatrix} |a| & |b| e^{j(\arg\{a\} + \arg\{b\})} \\ -|b| e^{-j(\arg\{a\} + \arg\{b\})} & |a| \end{bmatrix} \quad (6)$$

is left multiplied by \mathbf{R} , this yields zeros on the off-diagonal elements which achieves perfect polarization demultiplexing. The \sum operation in (3) and (5) averages our estimates over N training symbols. Furthermore, the differential phase between the two polarizations 2δ can be also estimated if we apply back the inverse of \mathbf{R}_1 to the received training symbols and estimate the common phase difference between the demultiplexed training symbols.

After polarization demultiplexing is achieved, we use the above estimates to set the initial center taps of a standard butterfly 2x2 equalizer whose remaining job is to mitigate any residual ISI. However, as polarization cross-talk is already mitigated, the constellations obtained by merely applying the inverse channel matrix estimated in (6) are quite good such that decision-directed (DD) error calculation can be used to update the taps of the butterfly filter using the LMS algorithm. This leads to ultrafast convergence as will be experimentally demonstrated.

Experimental setup and results

The proposed algorithm was verified experimentally for both 28 Gbaud PDM-QPSK and PDM-16QAM systems using the setup in Fig. 1a. The inphase (I) and quadrature (Q) signals were generated from either pulse pattern generators (PPGs) for PDM-QPSK or digital-to-analog converters (DACs) for PDM-16QAM. The I and Q signals were fed to a QAM transmitter to modulate an external cavity laser (ECL) laser having a linewidth less than 100 kHz. Single polarization power eye diagrams after the QAM transmitter are shown in Fig. 1b for both QPSK and 16QAM. Using a polarization beam splitter (PBS), an optical delay line (ODL) and a polarization beam combiner (PBC), PDM was emulated with a decorrelation delay of 324 symbols. The PDM signal was launched into an optical recirculating loop where each loop contains 4x80 km of SMF-28e+ low loss fiber and an erbium-doped fiber amplifier (EDFA) with 5 dB noise figure. Then, the output signal from the loop is filtered by a 0.4 nm filter, pre-amplified and re-filtered by a 0.4 nm filter before coherent reception. Coherent reception is done using a 90° optical hybrid that mixes the signal with CW light from an ECL laser similar to the one used at the transmitter where frequency offset between both lasers was below 500 MHz. After balanced detection, the four signals were sampled by two real-time scopes each running at 80 GSa/s for offline processing. Receiver side offline processing starts by IQ imbalance compensation followed by resampling to 2 samples per symbol, CD compensation using an FDE and frequency offset compensation using the periodogram method⁷. Phase noise was mitigated by a decision-directed phase locked loop (DD-PLL) with a loop coefficient of 0.02.

For polarization demultiplexing, we compare our proposed training symbol based channel estimation (TS-EST) with TS-LMS and CMA. After initial convergence is achieved by either TS-EST or TS-LMS, we switch to DD-LMS for steady-state operation. In case of CMA, we

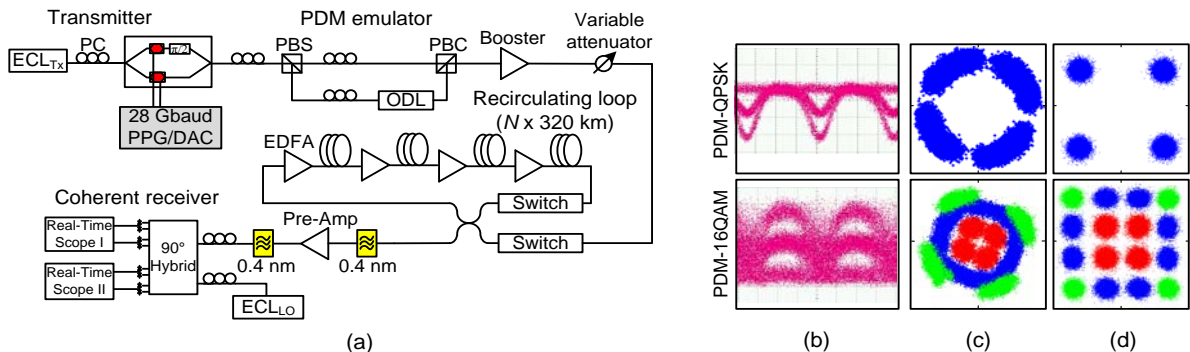


Fig. 1: (a) Experimental setup; (b) Power eye diagrams; (c) Constellations after polarization demultiplexing using the estimated inverse Jones matrix; (d) Constellations after processing with a DD butterfly equalizer and a PLL;

keep using it for steady-state operation for PDM-QPSK, whereas we also switch to DD-LMS for PDM-16QAM depending on when CMA starts to converge. Step sizes used are 1×10^{-3} , 1×10^{-3} and 4×10^{-4} for TS-LMS, CMA and DD-LMS, respectively. For TS-EST, we used 20 and 40 training symbols for PDM-QPSK and PDM-16QAM, respectively to estimate the Jones matrix. Fig. 1c shows the constellations after 320 km for both PDM-QPSK and PDM-16QAM obtained by merely applying the estimated inverse Jones matrix using the proposed TS-EST scheme, *i.e.* before the butterfly equalizer and the PLL. This proves that polarization demultiplexing is indeed achieved using very low TS overhead. This allows the subsequent butterfly equalizer to operate in DD mode if initialized according to TS-EST. Fig. 1d shows the final resulting constellations after the butterfly equalizer and the PLL. On the other hand, we always used 1500 training symbols for TS-LMS since it was the most needed to switch to DD-LMS in all collected data sets.

In Fig. 2, we first compare the three algorithms in steady-state operation for both PDM-QPSK and PDM-16QAM. Steady-state bit-error-rates (BER) are calculated excluding the convergence period. All algorithms achieve similar steady-state BER allowing us to transmit 5400 and 1000 km below a FEC threshold of 3.8×10^{-3} for PDM-QPSK and PDM-16QAM, respectively.

Secondly, the speed of convergence of the algorithms is compared. A smaller window of 20000 symbols over which BER is calculated is swept starting right after the training period. In case of CMA, the window was swept from the first symbol as no training is needed. Fig. 3 shows the results for PDM-QPSK at two different transmission distances of 4480 and 6080 km. Compared to TS-LMS, our proposed TS-EST scheme uses only 20 training symbols to achieve almost the same BER provided by TS-LMS using 1500 training symbols resulting in a huge reduction in TS length and very fast polarization tracking. Compared to around 2500 symbols needed by CMA, TS-EST achieves much faster convergence as well. It is also noteworthy that the speed of convergence achieved by our scheme does not depend on the SOP of the received light, whereas both TS-LMS and CMA might achieve a faster or slower convergence depending on the SOP, tap initialization and the step size parameter. Also, our scheme inherently does not suffer from any singularity problems and has the advantage that the transmitted X and Y polarizations are always recovered at the output X and Y polarizations, respectively. Finally, we compare all algorithms

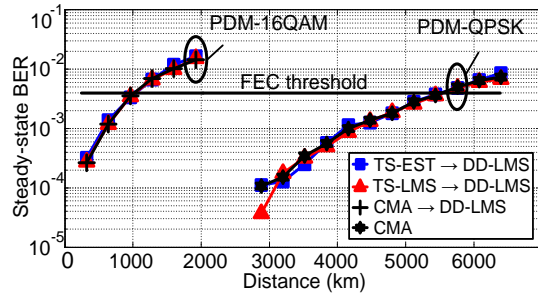


Fig. 2: Steady-state BER versus distance for all algorithms

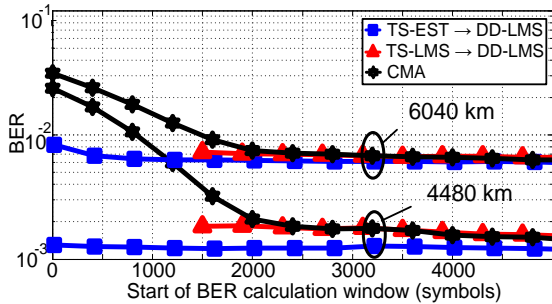


Fig. 3: Transient BERs of all algorithms for PDM-QPSK

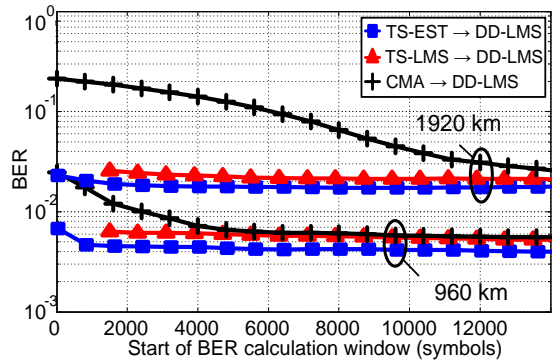


Fig. 4: Transient BERs of all algorithms for PDM-16QAM

for PDM-16QAM after 960 and 1920 km. As seen in Fig. 4, TS-EST needs 40 training symbols compared to 1500 for TS-LMS, whereas CMA needs around 3000 and 8500 symbols to achieve pre-convergence at both distances after which we switch to DD operation.

Conclusions

Training symbol based Jones channel matrix estimation is proposed. With fewer than 40 training symbols, tap adaptation of a butterfly equalizer can be started in DD mode. The proposed scheme is experimentally verified for 28 Gbaud PDM-QPSK and PDM-16QAM and found to achieve superior convergence speed compared to standard algorithms.

References

- [1] K. Roberts, IEEE Comm. Mag. **48**, 62 (2010).
- [2] S.J.Savory, JSTQE **16**, 1164 (2010).
- [3] E.M. Ip et al., JLT **28**, 502 (2010).
- [4] P.J. Winzer et al., JLT **28**, 547 (2010).
- [5] L. Liu et al., Proc. OFC'09, OMT2 (2009).
- [6] G. Agrawal, Light tech.: Telecom. sys (2005).
- [7] P. Ciblat et al., T. Comm. **54**, 1725 (2006).