PDL Insensitive Low-Complexity Equalizer for Digital Coherent Short-Reach Optical Transmission Systems

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Abstract: We propose and experimentally demonstrate a novel equalization algorithm based on Stokes space for short-reach digital coherent systems. It is robust to polarization-dependent loss (PDL), requires very little training overhead and the number of real multipliers is reduced by ~ 45%.

1. Introduction

In short-reach optical communication systems targeting intra-datacenter applications, intensity modulation and direct detection (IMDD) technique is always the priority selection because of low cost. However, coherent detection followed by digital signal processing (DSP) is now being considered because the limited bandwidth hinders further increasing the throughput of IMDD system [1]. For short-reach applications, the complexity and thus power consumption of DSP are a major concern.

The adaptive equalizer (AEQ) plays a vital role with multiple functions and typically consists of four complex-valued finite impulse response (FIR) filters with a butterfly configuration [2]. In order to reduce its complexity, K. Matsuda et al proposed a simplified AEQ (hereinafter called KM-AEQ) by dividing the N-tap FIR filters into two sections (as shown in Fig. 1 (a)), which is sensitive to the timing skew between in-phase (I) and quadrature (Q) or X-polarized and Y-polarized tributary channels [3]. J. Cheng et al further simplified KM-AEQ by replacing the N-tap complex-valued filters with the real-valued filters and introduced a post 3-tap T-spaced 4 × 4 MIMO real-valued FIR filter for the skew compensation [2]. However, the methods above are all based on constant modulus algorithm (CMA), which is sensitive to polarization dependent loss (PDL) [4]. In this paper, we propose a novel PDL insensitive AEQ based on Stokes space [5, 6] (as shown in Fig. 1 (b)), we experimentally verify that the performance of the proposed AEQ is similar to conventional 2 × 2 MIMO AEQ without post filter. In addition, the number of multiplications of proposed AEQ is the same as KM-AEQ (as shown in Tab. 1).

2. Proposed low-complexity AEQ based on Stokes space

2.1. Principle of polarization demultiplexing in Stokes space (SS-PDM)

According to [5,6], we briefly review the principle of SS-PDM as followed. Typically, as the optical waves propagate over the fiber, their polarization states evolve due to birefringence but remain nearly orthogonal. This is a simple consequence of optical fiber being relatively well approximated by a unitary matrix $M = \begin{bmatrix} a & b \\ -b^* & a^* \end{bmatrix}$. The elements a and b are complex and the determinant of the matrix M is equal to 1. Let us denote the received horizontal and vertical optical waves that emerge from the receiver's polarizing beam splitter by e_x and e_y, respectively. The Jones vector that represents the received optical wave is written as $E = \frac{1}{\sqrt{2}}\begin{bmatrix} e_x & e_y \end{bmatrix}^{-1}$ and it can be transformed into the Stokes vector $S = \begin{bmatrix} s_0 & s_1 & s_2 & s_3 \end{bmatrix}^{-1}$ [5]. The first component of the Stokes vector, s_0, represents the total power. The other three components s_1, s_2, s_3 represent 0° linear, 45° linear, and circularly polarized light, respectively. The theory of singular value decomposition (SVD) is applied to find the least squares plane (LSP) of the Stokes vectors and the normal of LSP is applied to calculate M^{-1} [5]. If the normal of LSP is $S : (s_1, s_2, s_3)$, the M^{-1} can be expressed as:

$$M^{-1} = \begin{bmatrix} \cos\left(\frac{\alpha}{2}\right)\exp\left(\frac{j\Delta\phi}{2}\right) & \sin\left(\frac{\alpha}{2}\right)\exp\left(-\frac{j\Delta\phi}{2}\right) \\ -\sin\left(\frac{\alpha}{2}\right)\exp\left(\frac{j\Delta\phi}{2}\right) & \cos\left(\frac{\alpha}{2}\right)\exp\left(-\frac{j\Delta\phi}{2}\right) \end{bmatrix} \tag{1}$$

Where $\Delta\phi = \arctan(s_3, s_2)$, and $\alpha = \arctan(s_2^2 + s_3^2, s_1)$. Once we have determined M^{-1}, we can conduct polarization demultiplexing by multiply the matrix and the signal vector, i.e. $M^{-1} \cdot \vec{E}$.

Based on the principle above, we replace the 1-tap filter by implementing the SS-PDM, the structure of the proposed AEQ (hereinafter called SS-PDM-AEQ) is shown in Fig. 1(b). Similar to KM-AEQ, the SS-PDM-AEQ also obtain a 2 × 2 matrix before the N-tap FIR filters. Therefore, the number of real multiplications per symbol of SS-PDM-AEQ is the same as that of KM-AEQ, i.e. $8N + 16$ (as shown in Tab. 1). Where N refers to the FIR tap length. In our simulation and experiment, the tap number is set at 21 so that the number is reduced by $(16\times21-8\times21-16)/(16\times21)\approx45\%$ compared with the conventional 2×2 MIMO AEQ.

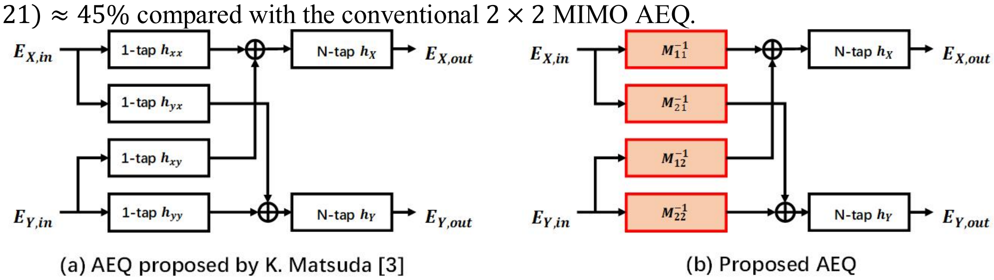

Fig. 1. (a) AEQ proposed by K. Matsuda [3]; (b) Proposed AEQ algorithm, where M^{-1} is the inversed unitary matrix computed by Eq. (1).

Table 1. Number of real multiplications per symbol

Method	Conventional 2×2 MIMO	KM-AEQ	Proposed AEQ
FIR filter	$16N$	$8N+16$	$8N+16$

2.2. Comparison between KM-AEQ and SS-PDM-AEQ in stability

In this section, we study the stability of KM-AEQ and SS-PDM-AEQ through simulation. When there exist PDL in the transmission system, it is possible that outputs from both ports converge with the same polarization tributary, which limits the performance of CMA-based polarization demultiplexing [4]. Let the unitary matrix expressing the fiber birefringence M be written as [4]:

$$M=\begin{bmatrix}\sqrt{\alpha}\exp(j\delta) & -\sqrt{1-\alpha}\\ \sqrt{1-\alpha} & \sqrt{\alpha}\exp(-j\delta)\end{bmatrix} \tag{2}$$

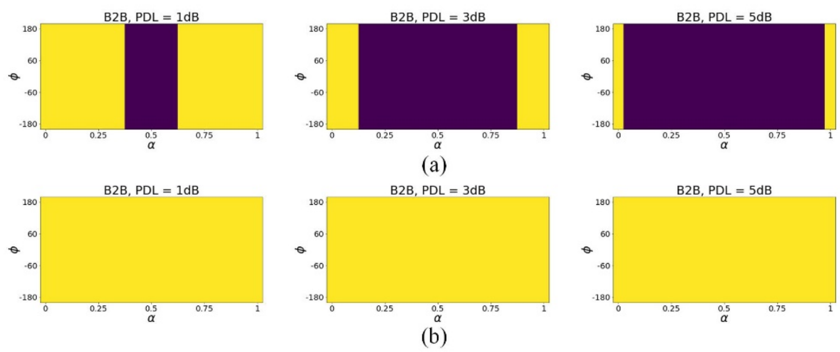

Fig. 2. Map of polarization demultiplexing stability with 1 dB, 3 dB, and 5 dB PDL. (a) KM-AEQ; (b) SS-PDM-AEQ

We set up the back-to-back (B2B) simulation system and transmit 12.5 Gbaud polarization-division-multiplexed 16-quadrature-amplitude-modulation (PDM-16QAM) signal. We change state of polarization (SOP) of the incoming signal by sweeping α and δ in the range where $0\le\alpha\le1$ and $-\pi\le\delta\le\pi$. We show polarization demultiplexing stability of KM-AEQ by a colored map on an $\alpha-\delta$ plane consisting of 10×20 segments (as shown in Fig. 2(a)). The dark area represents the cases that both ports converge with the same polarization tributary, and the light area represent the cases that the polarization demultiplexing is well done. We test the performance of KM-AEQ with 1 dB, 3 dB, and 5 dB PDL in the transmission system. It is obvious that the stability of KM-AEQ reduces as the PDL increases. On the other hand, the SS-PDM-AEQ do not suffer this penalty (as shown in Fig. 2(b)), we further experimentally verify the result in the next section.

3. Experimental verification

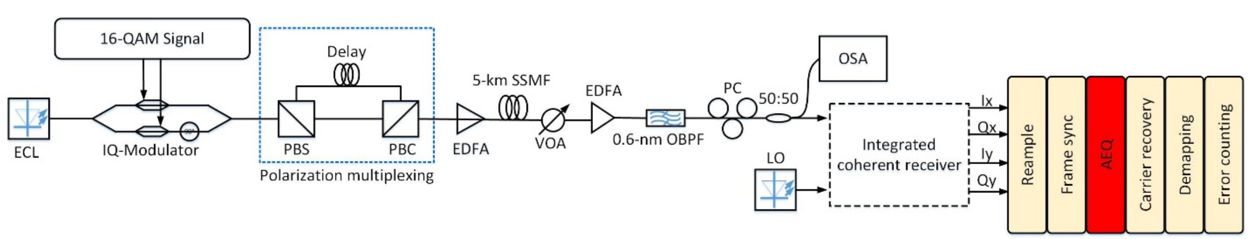

Fig. 3 Experiment set-up and DSP-flow.

The proposed SS-PDM-AEQ is experimentally verified by the system shown in Fig. 3. We generate 12.5 Gbaud PDM-16QAM optical signals by modulating a carrier signal, provided by an external cavity laser (ECL), using I/Q modulators which are driven by multi-level electrical signals. The center wavelength of ECL is 1552.52 nm and its line width is 100 kHz. Polarization multiplexing is then realized by utilizing polarization bean splitters (PBSs), polarization beam combiners (PBCs), and optical delay lines. The resulting signals are amplified using an erbium-doped fiber amplifier (EDFA) and sent over a 5 km long standard single-mode fiber (SSMF). A variable optical attenuator (VOA) is utilized to alter optical signal-to-noise ratios (OSNRs) in the range of 15 ~ 30 dB. The optical signals at the output of EDFA are filtered using a 0.6 nm optical band-pass filter (OBPF) and then detected by a coherent receiver. The electrical signals after optical-to-electronic (O/E) conversion are sampled by utilizing an oscilloscope with 50 Gsamples/s sampling rate and 2×10^6 samples are collected which are then processed offline. As for offline DSP, after being resampled to 2 samples per symbol and synchronized, the signals are fed into AEQ block with tap length of 21. Then carrier phase recovery is performed to remove frequency offset and phase noise. After the symbol mapping and decision, the bit error ratio (BER) is obtained by error counting.

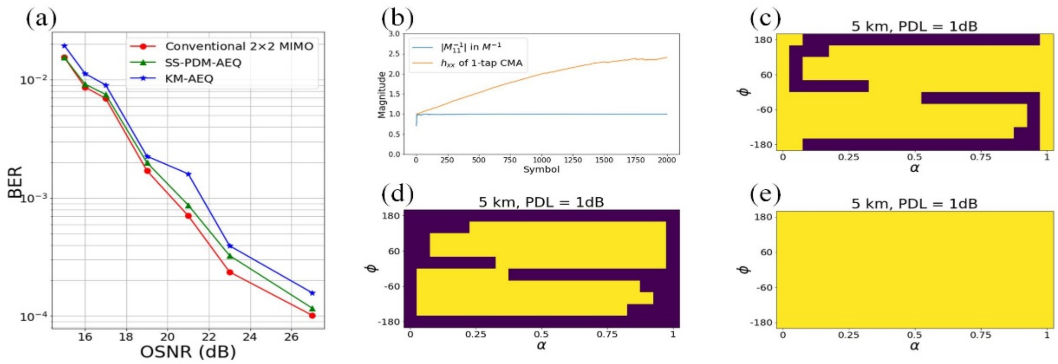

Fig. 4. (a) BER vs. OSNR using Conventional 2 × 2 MIMO, KM-AEQ and proposed SS-PDM-AEQ; (b) Convergence of SS-PDM-AEQ and KM-AEQ; (c) Map of polarization demultiplexing stability of conventional 2 × 2 MIMO; (d) Map of polarization demultiplexing stability of KM-AEQ; (e) Map of polarization demultiplexing stability of SS-PDM-AEQ.

The performances of SS-PDM-AEQ and conventional 2 × 2 MIMO AEQ as well as KM-AEQ are compared as shown in Fig. 4 (a). Compared with conventional 2 × 2 MIMO AEQ, the proposed SS-PDM-AEQ has a similar performance, which successfully verify its capacity. Fig. 4(b) analyzes the speed of convergence in polarization demultiplexing stage of KM-AEQ and SS-PDM-AEQ. It is obvious that SS-PDM-AEQ requires much less symbols to achieve stable performance, which indicates that SS-PDM-AEQ requires less training overhead. We further verify the stability of SS-PDM-AEQ by introducing PDL to the transmission system. In order to generate relatively concrete PDL, we adjust the power of one port of optical signals after PBSs by using a VOA and monitor the PDL value using a single module in offline DSP. The results with 1 dB PDL are shown in Fig. 4 (c), (d), (e). It is obvious that both conventional 2 × 2 MIMO AEQ and KM-AEQ suffers failure of polarization demultiplexing because they use CMA. On the other hand, the proposed SS-PDM-AEQ is insensitive to PDL and successfully perform polarization demultiplexing under different SOPs.

4. Conclusion

We propose and experimentally demonstrate a PDL insensitive and low-complexity equalization algorithm based on Stokes space. The polarization demultiplexing is performed by SS-PDM, and 2 complex-valued FIR filter are followed to further compensate the linear distortion. The proposed algorithm is proved to have better performance than KM-AEQ with the same complexity and much less training overhead. Also, it has similar performance compared with traditional 2 × 2 MIMO AEQ, while the number of multipliers can be reduced by ~ 45% when the tap number is set at 21. In addition, the stability of proposed SS-PDM AEQ is experimentally verified under 1 dB PDL.

5. Acknowledgements

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