Experimental Demonstration of PDL Insensitive Low-complexity Equalizer for Short-Reach Coherent Optical Transmission Systems

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Abstract: We propose and experimentally demonstrate a novel equalizer based on Stokes space for short-reach digital coherent systems. It is robust to polarization-dependent loss (PDL), shows extremely fast convergence speed, and reduces computational complexity significantly.

1. Introduction

In short-reach optical communication systems such as intra-datacenter and access network, intensity modulation and direct detection (IMDD) technique is always the priority selection because of its simple structure and low cost. Recently, coherent detection followed by digital signal processing (DSP) is now being considered because the limited bandwidth hinders further increase the throughput of IMDD system [1]. However, the complexity and power consumption of DSP in the receiver are a major challenge in short-reach applications.

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, 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) and shows very slow convergence speed [4]. Because the distribution of the polarization multiplexing signal in Stokes space is not affected by PDL [5,6], we propose a novel PDL insensitive AEQ based on Stokes space in this paper, which also has a fast convergence speed and low computational complexity. The experimental results show that the performance of the proposed AEQ is similar with that of conventional 2 × 2 MIMO AEQ. In addition, the number of multiplications of this proposed AEQ is also reduced significantly compared with the conventional method.

2. Principle

Typically, as the optical waves propagate over the fiber, their polarization states evolve due to birefringence but remain nearly orthogonal. The unitary matrix $M = [a\ \ b\,; -b^*\ \ a^*]$ can be utilized to express the fiber transmission matrix. The elements a and b are complex and the determinant of the matrix M is equal to 1. The received horizontal and vertical optical waves that emerge from the receiver's polarizing beam splitter are e_x and e_y, respectively. The Jones vector that represents the received optical wave is written as $E = \frac{1}{\sqrt{2}}\left[e_x\ \ e_y\right]^{-1}$ and it can be transformed into the Stokes vector $S = [s_0\ \ s_1\ \ s_2\ \ s_3]^{-1}$. 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. Singular value decomposition (SVD) is applied to find the least squares plane (LSP) of the Stokes vectors and the normal of LSP. If the normal of LSP is $S : (s_1, s_2, s_3)$, the M^{-1} can be found as [5]:

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

where $\Delta\phi = \arctan(s_3, s_2)$, and $\alpha = \arctan(s_2^2 + s_3^2, s_1)$. Polarization demultiplexing is realized by multiplying the matrix and the signal vector, *i.e.* $M^{-1} \cdot \vec{E}$. However, this polarization demultiplexing in Stokes space (SS-PDM) only has one tap which must assume that the transmission matrix is independent of frequency. As a result, the performance of this method will be degenerated by the polarization mode dispersion (PMD).

Fig. 1 (a) shows the structure of KM-AEQ, which firstly uses a 1-tap butterfly FIR filter for polarization demultiplexing and then uses two N-tap complex-valued FIR filters for the adaptive equalization. This approach could almost reduce computational complexity by half compared with conventional 2×2 MIMO AEQ. However, this method is sensitive to timing skew, random noise, and PDL. We replace the 1-tap filter by implementing the M^{-1} that calculated in Stokes space, 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 obtains a 2×2 matrix before the N-tap FIR filters. Therefore, the number of real multiplications per symbol of SS-PDM-AEQ is same with 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 experimental setup, the tap number is set at 21 so that the number is reduced by $(16 \times 21 - 8 \times 21 - 16)/(16 \times 21) \approx 45\%$ compared with conventional 2×2 MIMO AEQ.

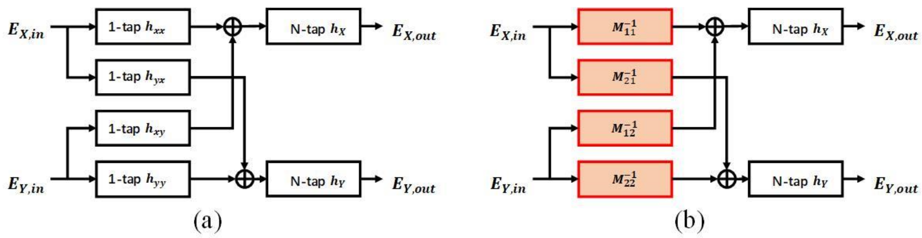

Fig. 1. (a) AEQ proposed by K. Matsuda [3]; (b) Proposed AEQ algorithm, where M^{-1} is the inversed unitary matrix computed by Eq. (1).

Table 1. Number of real multiplications per symbol

Method	Conventional 2×2 MIMO	KM-AEQ	Proposed AEQ
Number of real multipliers	$16N$	$8N + 16$	$8N + 16$

3. Comparison between KM-AEQ and SS-PDM-AEQ in Stability

When there is PDL in system, it is possible that outputs from both ports converge to the same polarization tributary, which limits the performance of CMA-based polarization demultiplexing [4]. The unitary matrix expressing the fiber birefringence M is written as $M = [\sqrt{\alpha}\exp(j\delta)\ \ -\sqrt{1-\alpha}\ ;\ \sqrt{1-\alpha}\ \ \sqrt{\alpha}\exp(-j\delta)]$ .We set up a back-to-back (B2B) simulation system and transmit 12.5 Gbaud polarization-division-multiplexed (PDM) 16QAM signal. We change state of polarization (SOP) of the incoming signal by sweeping $\alpha$and δ in the range where $0 \le \alpha \le 1$ 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.

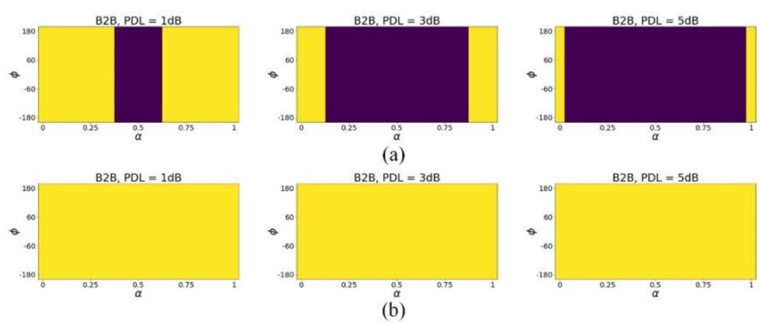

Fig. 2. Map of polarization demultiplexing stability with 1 dB, 3 dB, and 5 dB PDL. (a) KM-AEQ; (b) SS-PDM-AEQ

4. Experimental Setup and Results

The experimental setup is shown in Fig. 3. We generate the 12.5 Gbaud PDM-16QAM optical signal 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. A variable optical attenuator (VOA) is utilized to introduce PDL. The resulting signals are amplified using an erbium-doped fiber amplifier (EDFA) and sent over a 5 km long standard single-mode fiber (SSMF). Another 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. 2×10^6 samples are collected and 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.

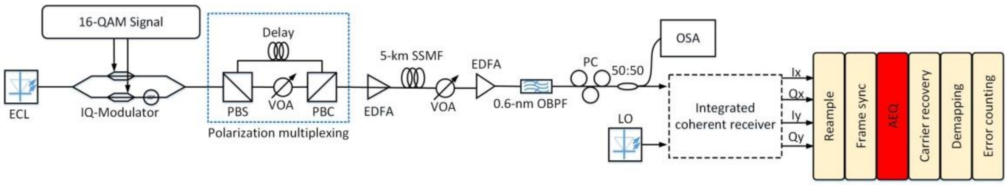

Fig. 3 Experimental setup and DSP-flow.

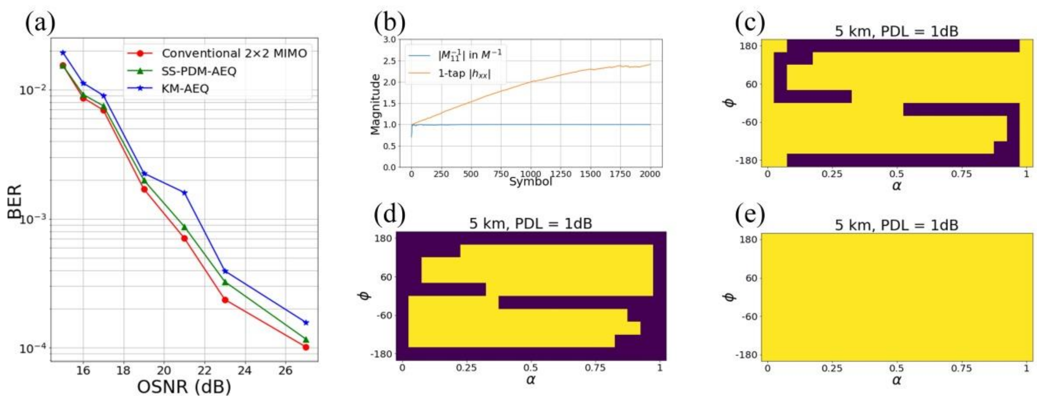

Fig. 4. (a) BER vs. OSNR using conventional 2 × 2 MIMO, KM-AEQ and proposed SS-PDM-AEQ, respectively; (b) Convergence speed of SS-PDM-AEQ and KM-AEQ; Map of polarization demultiplexing stability of (a) conventional 2 × 2 MIMO, (b) KM-AEQ, and (c) SS-PDM-AEQ.

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. 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 only tens of symbols to achieve stable performance, which indicates SS-PDM-AEQ is more adaptable to channel changes. 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 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 suffer failure of polarization demultiplexing. On the other hand, the proposed SS-PDM-AEQ is insensitive to PDL and can realize polarization demultiplexing successfully under different SOPs.

5. Conclusion

We propose and experimentally demonstrate a PDL insensitive and low-complexity equalizer based on Stokes space. The proposed approach is proved to show better performance than KM-AEQ with the same complexity. 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. The convergence speed of SS-PDM AEQ is much faster than the other two methods, which can adapt to more serious channel conditions. In addition, the stability of proposed SS-PDM AEQ is verified under 5 dB PDL in simulation and 1 dB PDL in experiment.

6. Acknowledgements

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