True Equalization of PDL in Presence of Fast RSOP

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Abstract: In presence of fast RSOP, a true PDL equalization including both signal power and OSNR balances is proposed and verified. With 1dB OSNR penalty, it can equalize up to 7dB PDL under 1Mrad/s fast RSOP. © 2020 The Author(s)
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1. Introduction

In long-haul polarization division multiplexing (PDM) systems, polarization dependent loss (PDL), which refers to polarization dependence optical power attenuation, may be a major factor limiting system performance. Some works tried to mitigate PDL with multiple-input-multiple output (MIMO) equalizer or Stokes Space method to balance the two polarization tributaries' power [1]. However, the signal distortion due to PDL not only means the inequality of signal power, but also the imbalance of signal-to-noise ratio (OSNR) between two polarization tributaries. The OSNR asymmetry will lead to quite different BER degradations and eventually deteriorate the overall system performance. Therefore, lots of PDL mitigation works in the literature were just power imbalance equalization, not the true PDL equalization [1-3]. One of the efficiently solution is to use polarization-time code (PTC) combined with the maximum likelihood (ML) detection [4]. Meanwhile, it was reported that in some extreme scenarios, like lightning strike, Kerr effect and Faraday effect would induce ultra-fast rotation of state of polarization (RSOP), as fast as mega-rad per second [5]. The combination of ultra-fast RSOP and PDL results in random and time dependent features. So, in presence of fast RSOP, the PTC method in [4] is not applicable because this method needs fast RSOP information which was unable to be tracked by the conventional method.

The Kalman filter (KF) was proved to be competent to track fast RSOP [6]. In this paper, we propose an equalization scheme for true equalizing the combined effects of PDL and fast RSOP by utilizing combination of PTC and KF. The results validate the proposed method is effectively to track RSOP and mitigate PDL.

2. Theory

2.1. The Effect of PDL in Presence of RSOP

PDL refers to the inequality loss values between its low and high loss eigen-modes. The transfer matrix can be modeled as

$$U_{PDL}=\begin{pmatrix}\cos\alpha & -e^{-j\delta}\sin\alpha\\ e^{j\delta}\sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}\sqrt{1-\rho} & 0\\ 0 & \sqrt{1+\rho}\end{pmatrix}\begin{pmatrix}\cos\alpha & -e^{-j\delta}\sin\alpha\\ e^{j\delta}\sin\alpha & \cos\alpha\end{pmatrix}^{-1}=\mathrm{R}_{eig}\Lambda\mathrm{R}_{eig}^{\;-1}\,. \tag{1}$$

$\Gamma_{dB}=10\log_{10}\left(1+\rho/1-\rho\right)$ is the PDL attenuation parameter. The two column vectors in R_{eig} denote the low/high loss eigen-modes of PDL.

PDL not only causes the inequality of signal power but also leads to OSNR imbalance of the two signal polarizations. Therefore, the true equalization of PDL should complete both the power equalization and the BER recovery coming from OSNR imbalance, as shown in Fig. 1(a). Unfortunately, lots of PDL equalizations only realized the former, leaving the OSNR imbalance unresolved.

In the optical fiber links, RSOP and PDL are generally coexisted. Generally accepted model is RSOP1 + PDL + RSOP2, in which RSOP1 and RSOP2 vary independently.

In summary, the true PDL equalization scheme in presence of RSOP we propose includes following 3 steps: (1) The simplification of model RSOP1 + PDL +RSOP2; (2) The power equalization using Stokes space, and the RSOP tracking using Kalman filter; (3) BER recovery using polarization-time code.

2.2. Fiber Model Simplification When PDL and RSOP are Coexisted

The matrix for model RSOP1 + PDL + RSOP2 can be described by Eq. (2).

$$\begin{aligned}\mathbf{H}&=\mathbf{R}_2\mathbf{R}_{eig}\mathbf{\Lambda}\mathbf{R}_{eig}^{-1}\mathbf{R}_1=\mathbf{R}_2\mathbf{R}_{eig}\mathbf{\Lambda}\mathbf{R}_{eig}^{-1}\cdot\left(\mathbf{R}_2^{-1}\mathbf{R}_2\right)\cdot\mathbf{R}_1=\left(\mathbf{R}_2\mathbf{R}_{eig}\right)\mathbf{\Lambda}\left(\mathbf{R}_2\mathbf{R}_{eig}\right)^{-1}\cdot\left(\mathbf{R}_2\mathbf{R}_1\right)\\&=\mathbf{R}_{new-eig}\mathbf{\Lambda}\mathbf{R}_{new-eig}^{-1}\cdot\mathbf{R}_{new-RSOP}=\mathbf{U}_{new-PDL}\cdot\mathbf{R}_{new-RSOP}.\end{aligned}\tag{2}$$

where $\mathbf{R}_2\mathbf{R}_{eig}$ constitutes the new eigen-modes of PDL originated from RSOP2, and $\mathbf{R}_2\mathbf{R}_1$ constitutes a new RSOP. So the simplified model can be viewed as new-RSOP + new PDL, as illustrated in Fig. 1(b). As such the PDL and RSOP are separated. Therefore, we can compensate for PDL at first and then RSOP.

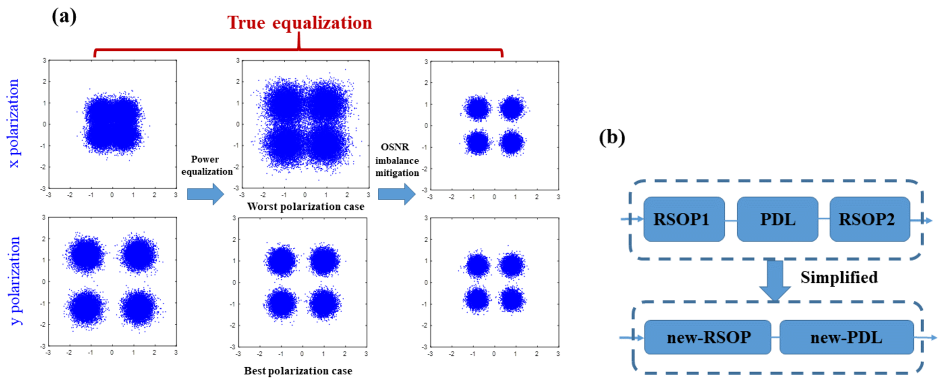

Fig. 1. (a) Constellation diagrams of PDL equalization. (b) The simplified model of RSOP combined with PDL.

2.3. *Balance of Power Inequality and RSOP*

The equalization of power inequality is based on the fact that the PDL induced power inequality will make the center of weight of a series of QPSK signal constellation points in Stokes space shifted from origin point. We can balance the PDL power inequality by three step re-shifting the center of weight in Stokes space as realized in Ref. [1]. The schematic diagram is shown in Fig. 2(b).

After PDL power equalization, we use an extended Kalman filter [7] to recover the RSOP induced impairment by choosing the state vector as $\vec{x}=(\kappa,\eta,\zeta)^T$, where κ, η and ζ are three angles which represent three-parameter RSOP, and by choosing the measurement innovation as

$$\boldsymbol{d}=\begin{bmatrix}0\\0\end{bmatrix}-\begin{bmatrix}\left(u_xu_x^*-r_1^2\right)\left(u_xu_x^*-r_2^2\right)\left(u_xu_x^*-r_3^2\right)\\\left(u_yu_y^*-r_1^2\right)\left(u_yu_y^*-r_2^2\right)\left(u_yu_y^*-r_3^2\right)\end{bmatrix}. \quad (3)$$

where u and u^* denote recovered signal and its conjugate, and r_1, r_2, r_3 denote the three radii of the constellations for Golden coded QPSK signal, as shown Fig. 2 (d).

2.4. *Equalization of OSNR Imbalance*

After power inequality balance and equalization of RSOP, OSNR imbalance which is aforementioned step (3) should be mitigated. This mitigation can be effectively realized by polarization-time (PT) codes, in which we make a linear combination of modulated symbols on two orthogonal polarizations. Here, we focus on the Golden code, which is a typical PT codes, the codeword matrix is:

$$X=\frac{1}{\sqrt{5}}\begin{bmatrix}\alpha\left(S_1+\theta S_2\right) & \alpha\left(S_3+\theta S_4\right)\\ i\bar{\alpha}\left(S_3+\bar{\theta}S_4\right) & \bar{\alpha}\left(S_1+\bar{\theta}S_2\right)\end{bmatrix}. \quad (4)$$

in which $\theta=\left(1+\sqrt{5}\right)/2$, $\bar{\theta}=\left(1-\sqrt{5}\right)/2$, $\alpha=1+i-i\theta$, $\bar{\alpha}=1+i-i\bar{\theta}$ and S_1,S_2,S_3,S_4 are information symbols.

At the receiver, ML detection is applied for symbol decision:

$$\tilde{X}=\underset{X\in A}{\operatorname{argmin}}\left\|Y-HX\right\|. \quad (5)$$

in which Y is the received symbols, A is the alphabet. H is the channel matrix.

Now the 3 steps are completed, and the PDL impairment in presence of RSOP is truly equalized.

3. Simulation and Analysis

The proposed scheme of true equalization of PDL in presence of RSOP is verified in a 28-GBaud PDM QPSK simulation platform, which is illustrated in Fig. 2. At the transmitter DSP, the Golden coding symbols is generated. Along the fiber, the optical signal experiences RSOP, PDL distortion, and ASE noise. At the receiver DSP side, the received signal is divided into two branches. The upper branch is used to obtain channel information. The PDL coefficients in Eq. (1) are estimated and power balance is implemented in Stokes space [1] at first, and then RSOP parameters are tracked by KF. The lower branch and channel information are fed into ML decoder for symbol decision according to Eq. (5).

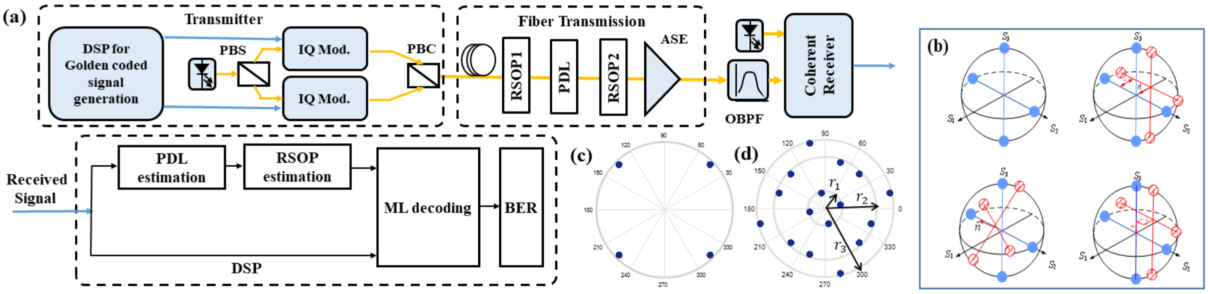

Fig. 2. (a) Simulation platform. (b) Schematic diagram of PDL estimation in Stokes Space. (c) Constellation diagrams of uncoded QPSK signal. (d) Constellation diagrams of Golden coded QPSK signal.

Figure 3 exhibits the performance of the proposed scheme (marked with Golden code+KF). As the comparison references, uncoded signal with CMA equalization method (Uncode+CMA), and Golden code with the training sequence assisted channel estimation method (Golden code+TS) are also utilized [4]. Figure 3(a) shows the BER performance with regard to OSNR with RSOP = 500krad/s and PDL = 3 dB. The results indicate that the proposed scheme provides the better performance than the uncode+CMA and Golden code+TS methods. The PDL induced OSNR penalty under severe impairment case of RSOP=1Mrad/s is studied in Fig. 3(b). Thanks to coding gain and the excellent dynamic tracking ability of KF, at the large value of approximate 7 dB PDL, the proposed Golden code+KF method only need about 1 dB OSNR penalty. The proposed scheme wins 2.8 dB OSNR (at BER=3.8×10^{-3}) compared with uncode+CMA method and 1.8 dB OSNR compare with Golden code+TS method. The results in Fig. 3(a) and (b) are the average BER for the best and worst polarization tributaries. Now we investigate the best and worst BERs for each polarization separately, as shown in Fig. 3(c), with OSNR=15dB, RSOP=1Mrad/s, PDL=6dB. Obviously, Golden code+KF method is very effective to equalize distortions especially for the worst polarization tributary, which dominates the total system performance.

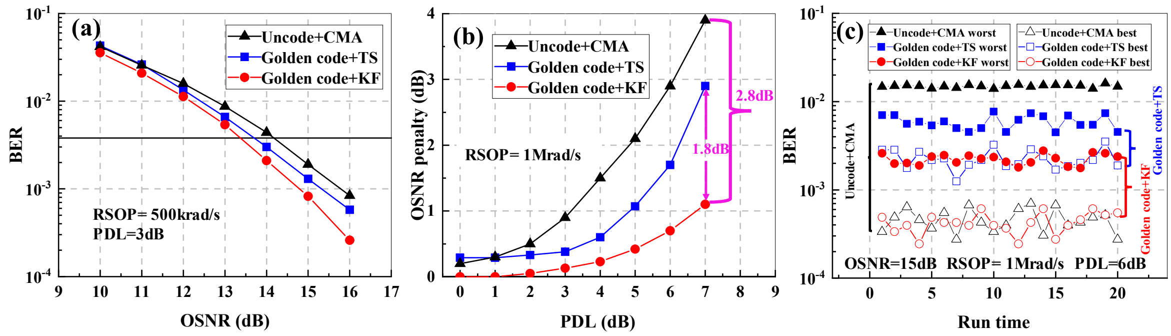

Fig. 3. (a) BER vs. OSNR. (b) OSNR penalty at BER= 3.8×10^{-3} . (c) BER performance for the best and worst polarization tributaries.

4. Conclusion

A true PDL equalization scheme in presence of fast RSOP is proposed using Golden code and Kalman filter, which provides excellent performance under the PDL as large as 6~7 dB combined with fast RSOP up to 1 Mrad/s.

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5. References

[1] N. Muga *et al.*, "Digital PDL Compensation in 3D Stokes Space," J. Lightwave Technol. vol. 31, pp. 2122-2130, 2013.
[2] S. Ishimura *et al.*, " Decision-Directed Adaptive PDL-Compensation Algorithm for Stokes Vector Receivers," ECOC, 2018.
[3] J. Zhou, *et al.*, "Constant modulus algorithm with reduced probability of singularity enabled by PDL mitigation," J. Lightwave Technol. vol. 35, pp. 2685-2694, 2017.
[4] S. Mumtaz *et al.*, " PDL Mitigation in PolMux OFDM Systems Using Golden and Silver Polarization-Time Codes," OFC, paper JThA7,2010.
[5] M. Kuscherov *et al.*, "Lightning affects coherent optical transmission in aerial fiber," Mar. 2, 2016. [Online].
[6] W. Yi *et al.*, " Joint Equalization Scheme of Ultra-fast RSOP and Large PMD in Presence of Residual Chromatic Dispersion," OFC, paper Th2A.51,2019.
[7] N. Cui *et al.*, "Two-parameter-SOP and three-parameter-RSOP fiber channels: problem and solution for polarization demultiplexing using Stokes space," Opt. Exp.vol. 26, pp. 21170-21183, 2018.