Side Effect of Normal Vector Recovery based Polarization Demultiplexing in Stokes Space and the Countermeasure

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Abstract *We deeply analyze the side effect of present polarization demultiplexing in Stokes space and propose an enhanced method by compensating residual phase retarder. Experiments show that the retarder compensation is indispensable and the proposed method tracks 1MHz polarization change with only 0.4dB Q penalty.*

Introduction

Polarization demultiplexing is very important in coherent optical receiver (Rx)[1]. The widely used polarization demultiplexing algorithms are constant modulus algorithm (CMA) and decision directed least mean squared (DD-LMS) algorithm[2]. Polarization demultiplexing can be also achieved in Stokes space by least-square plane fitting and normal vector recovery, which is a blind and modulation format free algorithm and immune to phase noise and frequency offset[3].

Conventional algorithms are designed to handle rotation of state of polarization (RSOP) with several tens of kHz, such as 45kHz polarization change induced by mechanical vibration[4]. However, in some risky events, such as lightning strike, the RSOP speed is up to ~810kHz[5]. Obviously, such high speed RSOP cannot be tracked by conventional algorithms. For fast polarization tracking, the normal vector estimation based on plane fitting is improved by the adaptive scheme[6] and Kalman filter is also applied[7]. Owning to the immunity to phase noise, the feedforward manner and low complexity than Kalman filter[8], the normal vector recovery in Stokes space may handle the high speed RSOP caused by lightning strike. However, there are several remaining challenges, such as the complexity of blind plane fitting, the ambiguity of normal vector direction and the interaction between the polarization recovery and the following digital signal processing (DSP).

In this paper, we deeply analyze the interaction between the polarization recovery and the following DSP, and find a significant side effect of polarization recovery in references[3],[6], which may completely fail the communication system. To overcome this side effect and the ambiguity issue, we propose an enhanced polarization recovery assisted by pilot symbol (PS). Experiment shows the proposed method has only 0.4dB Q penalty at 1MHz RSOP, which is enough to track fast polarization change in practical case.

Principle of proposed method

The dual polarization (DP) quadrature phase shift keying (QPSK) PS has been employed[9] to recover the carrier phase for various multi-level modulation format. Such existing PS is proposed for the enhanced polarization recovery.

At transmitter (Tx) side, the SOP of DP-QPSK PS has 4 points in Stokes space and the original normal vector $\vec{n_0}$ is [1, 0, 0] as shown in Fig. 1 (a). Due to RSOP and amplified spontaneous emission (ASE) noise in fiber channel, the 4 points are deviated from initial positions and scattered at Rx side as shown in Fig. 1 (b).

The principle of enhanced polarization recovery in Stokes space is to recover the received average SOP to the initial points. By comparing with the SOP of the transmitted PSs, the received 4-category SOP can be identified

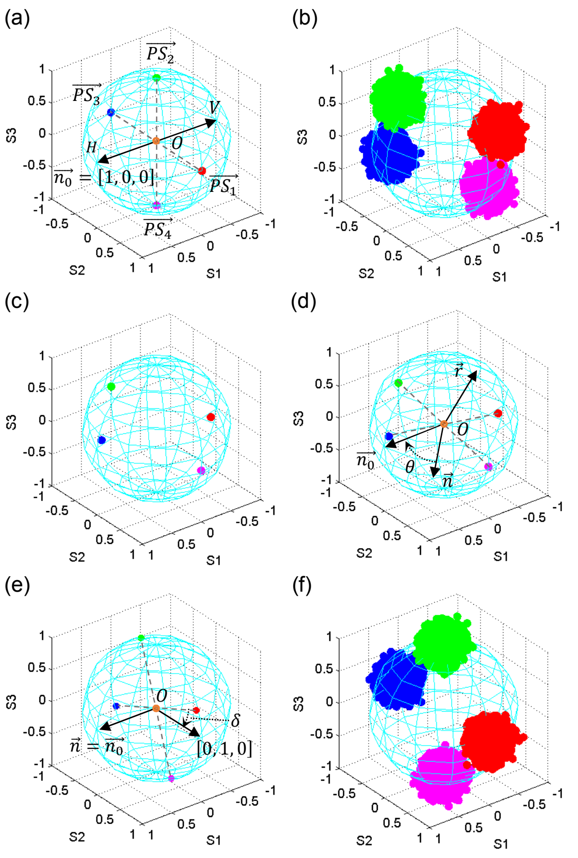

Fig. 1: Schematic of 4-category SOP in Stokes space. (a) Transmitted SOP, (b) received SOP, (c) SOP after averaging ASE noise, (d) normal vector recovery estimation, (e) residual retarder compensation estimation and (f) recovered SOP.

and labeled. The average SOP of each category is then obtained by averaging the ASE noise as shown in Fig. 1 (c). The normal vector of PS plane $\vec{n}$ is estimated by cross product between the two adjacent average SOP points, e.g. $\overrightarrow{PS_1} \times \overrightarrow{PS_2}$. Compared with the blind normal vector estimation based on the least-square plane fitting[3], the ambiguity of normal vector direction is eliminated and the computational complexity is reduced by the known PS.

Next, the SOP rotation is estimated to recover the normal vector $\vec{n}$ to its original vector $\overrightarrow{n_0} = [1, 0, 0]$. The geometrical illustration is shown in Fig. 1 (d).The normal vector $\vec{n}$ is rotated around the axis $\vec{r}$ with angle θ to align to original normal vector $\overrightarrow{n_0}$. The rotation axis $\vec{r}$ is the normalized cross product of the original and the present normal vectors, i.e. $\overrightarrow{n_0} \times \vec{n} / |\overrightarrow{n_0} \times \vec{n}|$. The angle θ is the angle between present normal vector $\vec{n}$ and original normal vector $\overrightarrow{n_0}$, which is calculated by $arccos(\overrightarrow{n_0} \cdot \vec{n} / |\overrightarrow{n_0}||\vec{n}|)$. It also means that the PS plane is back to S_2-S_3 plane as shown in Fig. 1 (e). By transforming such rotation in Stokes space to Jones space, the corresponding normal vector recovery matrix in Jones space is obtaiend.

$$M_{normal}^{-1} = cos\left(\frac{\theta}{2}\right)\boldsymbol{I} + jsin\left(\frac{\theta}{2}\right)(\vec{r} \cdot \boldsymbol{\sigma}) \qquad (1)$$

where $\boldsymbol{I}$ is identity matrix, $\boldsymbol{\sigma}$ is Pauli matrix.

Finally, the average SOP points of PS in S_2-S_3 plane is rotated back to their initial positions as shown in Fig. 1 (f). The coresponding operation in Jones space is a phase retarder.

$$M_{retarder}^{-1} = \begin{bmatrix} e^{j\delta/2} & 0 \\ 0 & e^{-j\delta/2} \end{bmatrix} \qquad (2)$$

where angle δ is the angle between present and initial average SOP points of each category as shown in Fig. 1 (e), e.g. $\overrightarrow{PS_1}$, and calculated by $arctan\left(\overrightarrow{PS_1}(3)/\overrightarrow{PS_1}(2)\right)$ in the range of $-\pi$ to π.

The retarder compensation is the main difference between proposed method and present methods[3],[6]. The residual phase retarder is the main reason of the side effect of present methods for the following DSP, i.e. carrier phase recovery (CPR).

Experimental setup

The experimental setup is shown in Fig. 2. The transmitted signal is 32GBaud DP-16 quadrature amplitude modulation (QAM) Nyquist signal with 0.15 roll-off factor, which is periodically inserted with DP-QPSK PS at the ratio of 1/32. The fast RSOP is achieved by electrical polarization controller (PC) with maximum rotation speed of 100kHz. The electrical PC and two polarization dependent loss (PDL) emulators are connected by manual PCs. The optical signal-to-noise ratio (OSNR) is set at 24dB by loading the lumped ASE noise. After coherent detection, the data captured by 80GSa/s is firstly processed by Gram-Schmidt orthogonalization procedure and then resampled to 2 samples per symbol and Rx skew is compensated. Next, it is processed by proposed method, pilot-assisted 17-tap 2x2 CMA, frequency offset compensation and pilot-assisted 4th-power CPR. The Q factor is calculated after decoding and decision.

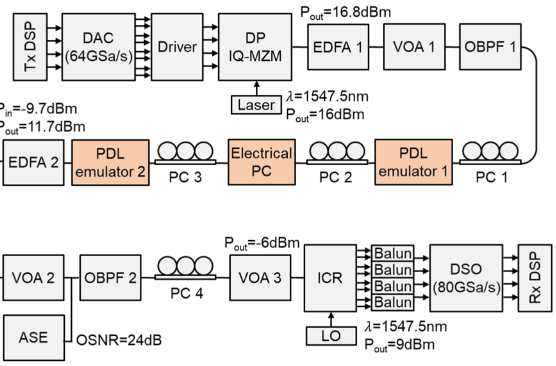

Fig. 2: Experimental setup. (DAC: digital-to-analog converter; IQ-MZM: in-phase/quadrature Mach-Zehnder modulator; EDFA: Erbium doped fiber amplifier; VOA: variable optical attenuator; OBPF: optical bandpass filter; LO: local oscillator; ICR: integrated coherent receiver; Balun: balanced to unbalanced transformer; DSO: digital storage oscilloscope)

Experimental results and discussion

First of all, we discuss the necessity of retarder compensation in Stokes space by using the polarization demultiplexing matrix in present methods[3],[6], which is the inverse of the RSOP model.

$$M^{-1} = \begin{bmatrix} cos(\alpha)e^{j\Delta\phi/2} & sin(\alpha)e^{-j\Delta\phi/2} \\ -sin(\alpha)e^{j\Delta\phi/2} & cos(\alpha)e^{-j\Delta\phi/2} \end{bmatrix} \qquad (3)$$

where $\alpha = \frac{1}{2} arctan(\vec{n}(1), \sqrt{\vec{n}(2)^2 + \vec{n}(3)^2})$ and $\Delta\phi = arctan\left(\vec{n}(2), \vec{n}(3)\right)$, which only recover the normal vector to $[1, 0, 0]$ and neglect the rotation in S_2-S_3 plane caused by residual phase retarder. Under some RSOPs as shown in Tab. 1, the residual RSOPs are existed after polarization demultiplexing by Eq. (3) and side effects are subsequently occurred.

In the case of I and II, the residual phase retarder causes constellation rotation for each polarization tributary. If the RSOP changes from case I to case II, the constellation rotation transfers to cycle slip and deteriorates CPR performance.

In the case of III, there is no polarization crosstalk and the normal vector is still aligned to $[1, 0, 0]$. In fact, the polarization demultiplexing is not necessary. However, ASE noise induced power fluctuation affects the normal vector estimation and transfers to phase noise by the estimated $\Delta\hat{\phi}$. We realize case III by tuning PC and obtain polarization demultiplexing matrix by

Eq. (3). The phase noise transferred by ASE noise is randomly distributed in the range of $-\pi/2$ to $\pi/2$ as shown in Fig. 3 and such kind of phase noise cannot be handled by CPR.

Besides, polarization rotation included the change of phase retarder. In the case of fast RSOP induced by lightning strike, the change of phase retarder is as fast as 1MHz in some case. The CPR designed for phase noise of 100kHz cannot process such high speed phase noise.

In proposed method, the compensation for residual phase retarder recovers the average SOP of received signal to its original position and overcomes all above side effects.

Tab. 1: Residual RSOP when side effect occurrs.

Range of rotation angle	Residual RSOP $\widehat{M}^{-1}M$	
	Present method[3],[6]	Proposed method
I. $\alpha \in (-\frac{\pi}{2}, 0)$ $\Delta\phi \in (-\pi, 0)$	$\begin{bmatrix} j & 0 \\ 0 & -j \end{bmatrix}$	$\boldsymbol{I}$
II. $\alpha \in (-\frac{\pi}{2}, 0)$ $\Delta\phi \in (0, \pi]$	$-\begin{bmatrix} j & 0 \\ 0 & -j \end{bmatrix}$	$\boldsymbol{I}$
III. $\alpha = 0$ $\Delta\phi \in (-\pi, \pi]$	$\begin{bmatrix} e^{j\frac{\Delta\hat{\phi}-\Delta\phi}{2}} & 0 \\ 0 & e^{-j\frac{\Delta\hat{\phi}-\Delta\phi}{2}} \end{bmatrix}$	$\boldsymbol{I}$

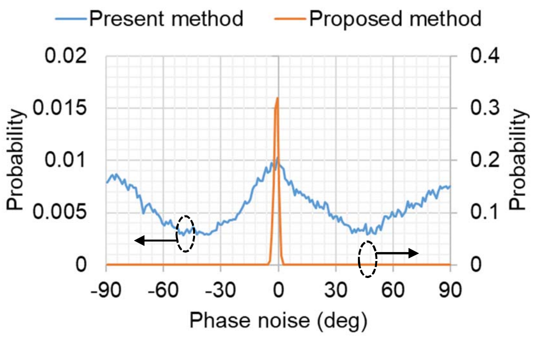

Fig. 3: Phase noise transferred by ASE noise in case III.

Then, we evaluate the performance of proposed method in fast RSOP. The update rates of the proposed method and CMA are decreased from every 1 to every 10 PS to emulate fast RSOP from 100kHz to 1MHz. The CMA step size and CPR block size are optimized. The average length of proposed method is fixed to 201. By tuning PC, fast RSOP with different rotation axis can be obtained. In Fig. 4, compared with 100kHz RSOP at different rotation axis, only 0.4dB Q penalty is induced by 1MHz RSOP for CMA with proposed method. It indicates that the proposed method achieves fast polarization tracking at arbitrary RSOP. Meanwhile, more than 5dB Q improvement at 1MHz is achieved by proposed method. Obviously, it has much higher tracking ability for fast polarization change and enough to handle practically observed ~810kHz RSOP in reference[5] with acceptable Q penalty.

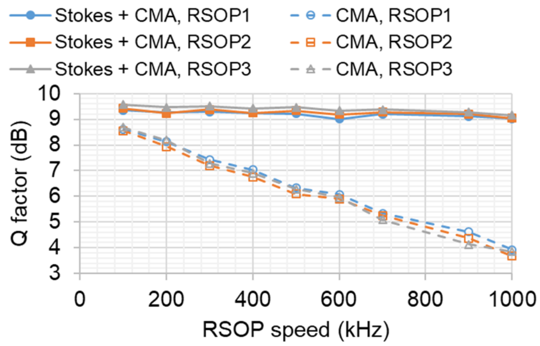

Fig. 4: Q factor in fast RSOP.

We further investigate the performance of proposed method in both fast RSOP and PDL. In practical, the lightning strike induced fast RSOP is randomly occurred in link. Therefore, the total 4dB PDL is added by two PDL emulators with three distributions, i.e. (0dB, 4dB), (2dB, 2dB) and (4dB, 0dB), to emulate the position of fast RSOP at the beginning, middle and end of link. In Fig. 5, compared with 100kHz RSOP at each RSOP position, CMA with proposed method has about 0.5dB Q penalty at 1MHz RSOP. Only 0.1dB extra Q penalty for tracking 1MHz RSOP in presence of 4dB PDL. It should be noted that the PDL is compensated by using method in literature[10].

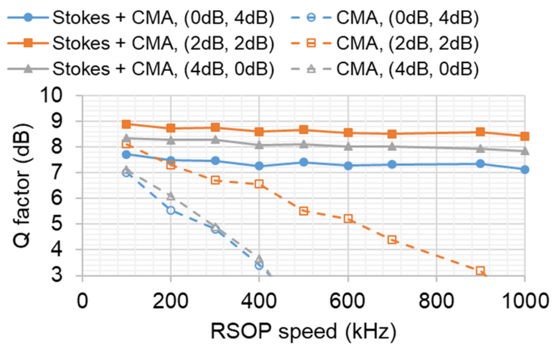

Fig. 5: Q factor in fast RSOP and PDL.

Conclusion

In this paper, we analyze the side effect of present normal vector recovery based polarization demultiplexing in detail and propose a pilot assisted enhanced method. The ambiguity of normal vector direction is eliminated and the residual retarder is compensated. Experimental results show that the retarder compensation is indispensable in both static and dynamic RSOPs. The proposed method tracking 1MHz RSOP with only 0.4dB Q penalty compared with performance at 100kHz RSOP. In presence of 4dB PDL, 1MHz RSOP at arbitrary position of link can be tracked with only extra 0.1dB Q penalty, which further demonstrates the proposed method is useful in practical scenario.

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