An Accurate and Robust PDL Monitor Method Based on Sliding Window Least Square Algorithm

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***Abstract*—In this paper, we proposed a PDL monitoring and correction method based on sliding-window least-square algorithm. Numerical simulation results show that both the polarization equalization and monitoring effects are better than those based on CMA.**

Keywords—polarization dependent loss monitoring, sliding window least square algorithm, optical communication systems.

I. Introduction

In the polarization division multiplexing (PDM) coherent optical communication system, polarization dependent loss (PDL) is one of the most critical polarization impairments. PDL causes non-orthogonality and power imbalance between the two transmitted polarization tributaries and thus leads to increase of the bit error ratio (BER), such that a higher optical signal-to-noise ratio (OSNR) margin is required for the system performance [1]. In addition, distributed PDL also changes with time due to the time-varying rotation of states of polarization (RSOP). PDL monitoring should be dynamically adaptive to its temporal changes.

Several monitoring algorithms have been proposed in literature, such as the CMA coefficients aided [2, 3], pilot aided or training sequence aided methods [4, 5] and the 3D-Stokes method [6]. The pilot-aided monitoring algorithm realizes high accuracy by inserting pilot symbols (clockwise and anticlockwise rotating QPSK symbols, CAZAC sequences, etc.) to remove the impact of noises and recover channel transmission responses. However, extra data cost is required for pilot symbols, which would decrease the spectrum efficiency. Inserting the pilot sequence needs to change the frame structure, thus increasing the challenge of frame synchronization. For the 3D Stokes method, a large number of symbols are needed to accurately find the plane (where the constellation points are located) and its normal vector. If the speed of RSOP is fast, the plane would become vague and thus cannot accurately reflect the temporal change of PDL. Monitoring by DSP algorithms is one of the most direct methods, where the monitoring function is embedded in the equalization algorithm. Therefore, the performance of monitoring obviously depends on the performance of equalization, and failed equalizing leads to failed monitoring. As the most widely used polarization equalization algorithm, CMA has a severe problem of singularity when the PDL is large, which leads to the failure of polarization equalization and thus the failure of PDL monitoring.

In this paper, we proposed a PDL monitoring method based on the sliding window least square (SW-LS) algorithm, and a method to correct the monitoring error by fitting a high-order polynomial of error distribution. Numerical simulation results proves that the proposed monitoring method has a better monitoring accuracy and stronger robustness in a wide range of PDL.

II. PDL Monitoring Based on SW-LS Algorithm

The core idea of our PDL monitoring method is to estimate the channel matrix $\mathbf{H}$ associated with PDL by digital signal processing (DSP) algorithms and then calculate the PDL value. Once the DSP algorithm reaches its convergence and the channel matrix is estimated as $\hat{\mathbf{H}}$, the singular value decomposition (SVD) can be performed to give

$$[\mathbf{U}, \mathbf{\Sigma}, \mathbf{V}^{\dagger}] = \mathrm{svd}\left(\hat{\mathbf{H}}\right) \tag{1}$$

where the columns of matrices $\mathbf{U}$ and $\mathbf{V}$ are respectively the output and input principal modes of polarization (PMPs), and $\mathbf{\Sigma}$ is a diagonal matrix containing the information of PDL. Therefore, the estimation value of PDL in dB can be calculated as

$$\mathrm{PDL}_{\mathrm{dB}} = 20\log_{10}\left(\frac{s_1}{s_2}\right) \tag{2}$$

where $s_{1,2}$ are the two non-zero entries of $\mathbf{\Sigma}$ with $s_1 > s_2$.

Generally, the PDL of optical devices is static and the standard least squares algorithm is applicable for the estimation of the deterministic channels. However, the PDL value changes with time when there exists time-varying RSOP, and the SW-LS algorithm is required to adaptively track and equalize the dual-polarization PDL channel [7]. Considering the PDL and RSOP impairments in fiber links, the evolution of the channel transmission matrix can be expressed as

$$\mathbf{H}_{k+v} = \mathbf{G}_k \mathbf{H}_k \tag{3}$$

where $\mathbf{H}_k$ and $\mathbf{H}_{k+v}$ represent the channel matrix at the instance k and $k+v$, respectively. $\mathbf{G}_k$ is a 2×2 complex matrix containing the overall RSOP effect and the aggregated PDL since the instance k. Choice of the time step length v, which is related to the speed of RSOP, is important because it directly affects the performance of monitoring. The PDL value is essentially unchanged during the time from k to $k+v$ if v is small, however, if v is too large, the PDL value would change a lot, leading to failure of tracking and inaccuracy of monitoring. We respectively define the $2\times L$ matrix of the received symbols $\mathbf{X}_k$ and the $2\times L$ matrix of the estimated received symbols $\hat{\mathbf{S}}_k$ as

$$\begin{aligned} \mathbf{X}_k &= \left[\underline{\mathbf{x}}_k, \underline{\mathbf{x}}_{k+1}, \dots, \underline{\mathbf{x}}_{k+L-1}\right] \\ \hat{\mathbf{S}}_k &= \left[\hat{\underline{\mathbf{s}}}_k, \hat{\underline{\mathbf{s}}}_{k+1}, \dots, \hat{\underline{\mathbf{s}}}_{k+L-1}\right] \end{aligned} \tag{4}$$

where L is the length of the equalization window. L and v jointly determine the convergence speed, equalization effect and complexity of the algorithm, and v is generally smaller than L to ensure an overlap between the equalization windows. Within each equalization window, the symbols $\hat{\underline{\mathbf{s}}}$ can be updated by the estimation of channel matrix of the previous instance according to the minimum Euclidean distance criterion,

$$\hat{\underline{\mathbf{s}}}_{k+l} = \arg\min_{\underline{c}} \left\| \hat{\mathbf{H}}_k^{-1} \underline{\mathbf{x}}_{k+l} - \underline{c} \right\|^2 \tag{5}$$

where $\underline{c}$ is the ideal point of the transmitted signals. The channel estimation can be defined as

$$\arg\min_{\hat{\mathbf{G}}_k} \left\| \mathbf{X}_k - \hat{\mathbf{G}}_k \hat{\mathbf{H}}_k \hat{\mathbf{S}}_k \right\|^2 \tag{6}$$

and the optimal solution of Eq. (6) is given by the LS algorithm as

$$\hat{\mathbf{G}}_k = \mathbf{X}_k \hat{\mathbf{S}}_k^\dagger \hat{\mathbf{H}}_k^\dagger \left(\hat{\mathbf{H}}_k \hat{\mathbf{S}}_k \hat{\mathbf{S}}_k^\dagger \hat{\mathbf{H}}_k^\dagger \right)^{-1} \tag{7}$$

where the estimation of channel matrices is initialized as the identity matrix $\hat{\mathbf{H}}_0 = \mathbf{I}_2$. Insert Eq.(7) into (3) and one can get the update of channel matrix estimations. Therefore, the channel matrices are estimated adaptively and the PDL can be monitored dynamically for the time-varying channel.

III. Simulations and Analyses

A. PDL channel emulation platform constructions

To verify the effectiveness of the proposed monitoring method, we must at first construct a time-varying PDL channel emulation platform and a coherent optical communication system working on it, as shown in Fig. 1. The PDL fiber channel is composed of *N* spans (each containing a PDL element), two time-varying RSOP hinges and an amplified spontaneous emission (ASE) noise source. For a given mean PDL of the fiber channel $\langle \Gamma_{\mathrm{dB}} \rangle$, the PDL value of each span Γ_i is allocated by

$$\Gamma_i = \sqrt{\frac{3\pi}{8N}} \left(1 + \sigma x_i\right) \langle \Gamma_{\mathrm{dB}} \rangle \tag{8}$$

where x_i are N random numbers satisfying Gaussian distribution with mean value 0 and variance σ.

A three-parameter model is deployed to construct the RSOP hinges, which can be expressed as [8]

$$\mathbf{J}_i = \begin{bmatrix} \cos\kappa_i e^{j\xi_i} & -\sin\kappa_i e^{j\eta_i} \\ \sin\kappa_i e^{-j\eta_i} & \cos\kappa_i e^{-j\xi_i} \end{bmatrix} \tag{9}$$

where κ is the azimuth rotation angle, and ξ, η are phase rotation angles. To generate a time-varying RSOP matrix, we set these three independent parameters as functions changing with time *k*,

$$\begin{aligned} \kappa_i &= \omega_{\kappa_i} k + \theta_{\kappa_i} \\ \xi_i &= \omega_{\xi_i} k + \theta_{\xi_i} \\ \eta_i &= \omega_{\eta_i} k + \theta_{\eta_i} \end{aligned} \tag{10}$$

where $\omega_{\kappa_i}, \omega_{\xi_i}, \omega_{\eta_i}$ are the rotation speeds of the three angles of the *i*th hinge, respectively, and $\theta_{\kappa_i}, \theta_{\xi_i}, \theta_{\eta_i}$ are the initial angles which satisfy the random distribution over $[0, 2\pi]$. Symbols are generated at the rate of 140Gbaud at the transmitter, and the proposed PDL monitoring method is deployed at the receiver side. For comparison, the CMA is chosen as another polarization equalization algorithm and the PDL values can also be monitored by its tap coefficients.

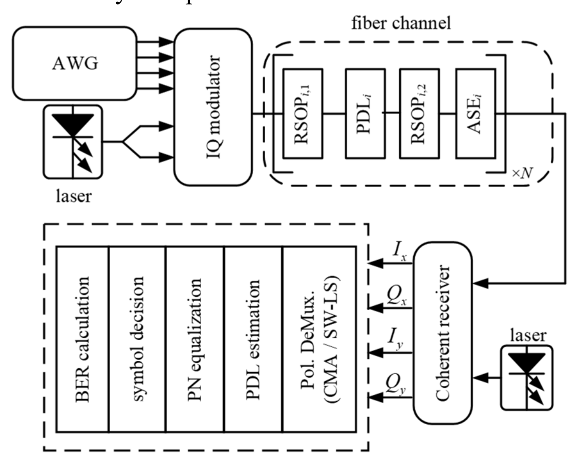

Fig. 1. Diagram of the simulation platform.

B. PDL monitoring and error correction

As shown in Fig. 1, the polarization-effect equalization is performed by the SW-LS algorithm or CMA after the coherent receiver. When the algorithms reach their convergence, the tap coefficients of CMA or the channel matrix estimations of SW-LS are extracted regularly to monitor the real-time PDL values. Monitoring results of the two algorithms are exhibited in Fig. 2.

The red solid line represents the true PDL values in the channel, the blue plus marks and yellow dots denote the PDL estimations acquired by the SW-LS and CMA, respectively. Estimated channel matrices by the SW-LS or tap-coefficients of the CMA are extracted for every single symbol. It is intuitive that the monitoring result by the SW-LS should fit the true PDL curve better than that by the CMA. For verification, mean values are taken for every 2^9 monitoring results and are plotted in the figure, with the green dashed line for the SW-LS and the black dotted line for the CMA. It is obvious that the temporal mean values of the monitoring results by SW-LS are almost perfectly coincident with the true PDL values, whereas those by the CMA show a clear deviation, indicating that the SW-LS is more accurate and has faster responses to the temporal channel impairment changes than CMA.

In practice, we only need to report the PDL monitoring values at set intervals instead of giving them by every single symbol. Here, we perform stochastic simulations with 2^{16} symbols each time and the PDL estimation values are calculated every 2^6 symbols. Then we take the mean value of all calculated PDL estimations as the reporting value. Notice that even though the transmission time for 2^{16} symbols is also very short compared to the required monitor time in real scenario, the data size does make sense statistically. We set the mean PDL $\langle \Gamma_{\mathrm{dB}} \rangle$ in Eq. (8) as 1, 3 and 5dB and perform 5000 Monte Carlo stochastic simulations, respectively. Monitoring error is defined as the difference between the temporal mean values of the monitored PDL and true PDL of the channel, and all the 15000 monitoring errors of the SW-LS and CMA are depicted in Fig. 3. Compared with the CMA, the monitoring error values by the SW-LS are generally smaller. Moreover, the distribution of monitoring errors by SW-LS is narrower than the CMA. For example, at the position of monitoring PDL = 4 dB, the difference between the maximum and the minimum error by the SW-LS is about 0.3 dB, while that by the CMA is as large as 1.3 dB. Moreover, with the increase of PDL, the monitoring error by the CMA increases rapidly and approximately reaches 3 dB when the monitoring PDL value goes to 10 dB. As for the SW-LS, the monitoring error still remains below 0.5 dB even when the PDL monitoring value exceeds 10 dB. In addition, another problem for the CMA is the singularity. It can be seen that for the CMA, the number of monitoring points decreases significantly when PDL monitoring value is larger than 6 dB. This is because in the presence of large PDL, the CMA is prone to singularity problems, which may cause polarization demultiplexing failures and cannot obtain the right PDL values by tap coefficients. In these cases, the monitoring errors may be as high as tens of dB, thus make no sense and have been deleted from the figure. To demonstrate that the SW-LS has better polarization demultiplexing ability, we choose several channel states which the CMA cannot demultiplex successfully, and try to process by the SW-LS. The SW-LS can equalize these channels successfully and maintain reasonable BER.

It is worth noting that for small PDL less than 2 dB, monitoring errors increase rapidly with the decrease of PDL for both the SW-LS and CMA. Moreover, the monitoring values meet a cut-off at the position of around 1 dB, which means the minimum reporting PDL by the monitoring algorithm is approximately 1 dB, no matter how small the real PDL is. To solve the problem, we consider fitting the monitoring errors using a high-order polynomial and correcting the monitoring values according to the fitted polynomial. To verify if the correction polynomial is related to channel models and which factors would affect the polynomial, we calculate monitoring error distributions under different channel models and plot them in Fig. 4. For channels without ASE noise, the monitoring error distributions of channels with different span numbers are almost identical, which means that the correction polynomial is not related to the RSOP speed. Besides, for channels with the same span number and RSOP speed, the correction polynomials change with optical signal-noise ratio (OSNR). Therefore, OSNR is the only factor influencing the correction polynomial, and we just need to choose the corresponding one to correct the monitoring results once the OSNR of the optical communication system is determined. Although we can also get a correction polynomial according to the error distribution for the CMA, the range of monitoring errors is too wide to correct the results accurately by the polynomial.

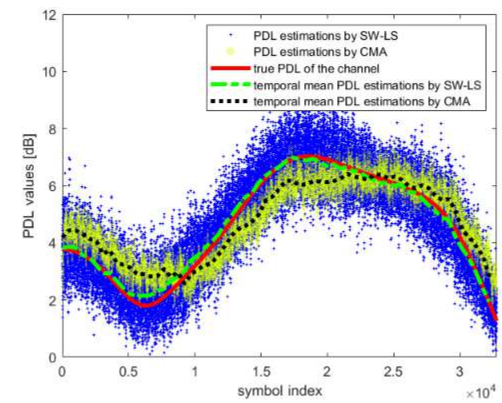

Fig. 2. Comparisons between true PDL values in fiber channel and PDL monitoring results by SW-LS or CMA.

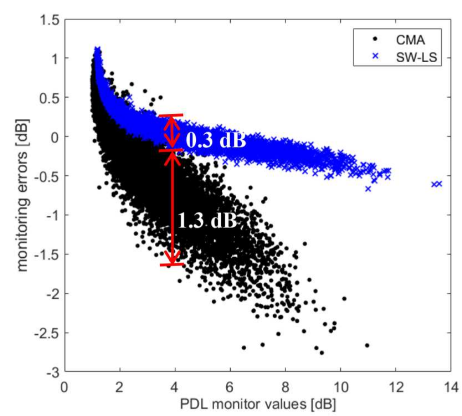

Fig. 3. Distribution of monitoring errors by CMA and SW-LS in 15000 Monte Carlo stochastic simulations, with OSNR as 19.7 dB.

As shown in Fig. 5, we perform 100 stochastic numerical simulations and set the mean PDL $\langle \Gamma_{\mathrm{dB}} \rangle$ as 3dB, the total RSOP speed as 0.35 Mrad/s, and the OSNR as 19.7 dB. When the correction polynomial is applied in the monitoring algorithm, the monitoring error of 100 simulations is stable around 0, even when the PDL is smaller than 1 dB.

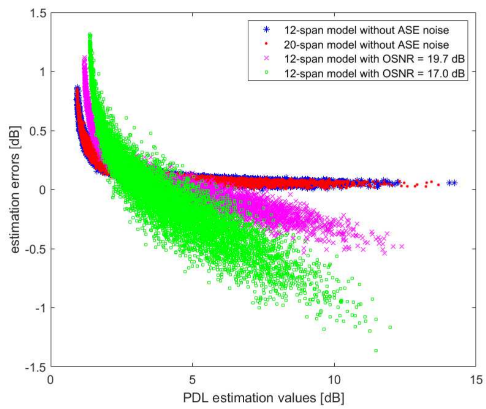

Fig. 4. Relationship between the correction polynomial acquired by SW-LS and the RSOP speed or OSNR.

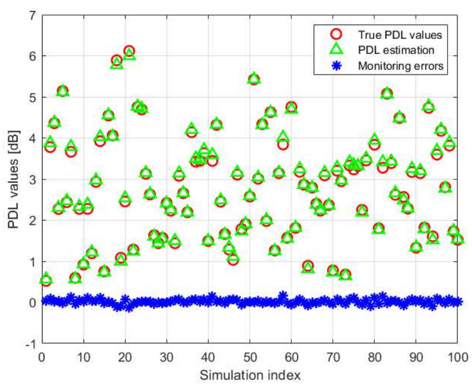

Fig. 5. Monitoring results of 100 stochastic simulations applying correction polynomial in the monitoring algorithm based on SW-LS.

IV. SUMMARY

We proposed a PDL monitoring method based on the SW-LS algorithm, and solved the problem of monitoring inaccuracy for small PDL values by correction polynomials. Numerical simulation results show that the monitoring algorithm has much higher accuracy and robustness than the widely used CMA. When the average PDL of the fiber link is set to 1 dB, the ratio of the monitoring error obtained by the CMA to the true PDL value is 26.81%, while that of the SW-LS is only 1.58%. In addition, we proposed a polynomial-based correction method for monitoring errors when the PDL is small, and the errors are kept near 0 under small PDL. The proposed PDL monitoring algorithm shows good dynamic tracking characteristics under high-speed RSOP and thus can provide reliable basis to adjust OSNR of the communication system.

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