Two-Stage Constant Modulus Algorithm Equalizer for Singularity Free Operation and Optical Performance Monitoring in Optical Coherent Receiver

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Abstract: A two-stage constant-modulus-algorithm (CMA) equalizer for polarization-demultiplexing in a polarization-division-multiplexed coherent receiver is demonstrated. The equalizer eliminates the singularity problem of CMA equalizers and provides an effective way to monitor polarization-mode dispersion and polarization-dependent loss.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications; (260.5430) Polarization

1. Introduction

Polarization-division-multiplexed (PDM) optical coherent systems with digital signal processing is considered a promising technique for next generation optical networks [1][2]. With coherent detection, various transmission impairments can be compensated in the electrical domain by high-speed electronic equalizers. Powerful and efficient equalization algorithms are crucial for optical coherent detection. Constant modulus algorithm (CMA), due to its simplicity and immunity to phase noise, has been widely used in coherent receivers, not only for phase modulation signals, but for quadrature amplitude modulation signals as well [2][4]. However, a CMA equalizer has the singularity problem in that the two outputs of the polarization demultiplexing equalizer could converge to the same source [3][5]. Two techniques have been proposed to solve the problem. One technique is to monitor the determinant of the Jones matrix of the equalizer such that if it begins to approach zero the equalizer resets [3], and the other technique is to carefully choose the initial tap values for the CMA equalizer [5]. While these solutions can be used in offline processing, they may cause outages in a real system when reinitializing the tap values.

The parameters of the equalizers in a coherent receiver can be used to estimate channel parameters, such as polarization-mode dispersion (PMD) and chromatic dispersion. As the transfer function of the equalizers are usually not exactly inverse of a channel transfer function, typically the methods that directly use equalizer parameters for channel estimation require sophisticated data fitting and have large estimation errors [6][7].

In this paper, a two-stage CMA equalizer is proposed for polarization demultiplexing in a coherent receiver. It not only eliminates the singularity problem of an ordinary CMA equalizer, but provides an effective way to monitor PMD and PDL in the system as well. The technique is demonstrated with both simulations and experiments.

2. Two-Stage CMA Equalizer

Fig. 1 depicts a PDM optical coherent communication system, where the two-stage CMA equalizer is used in the coherent receiver. In the first stage of the equalizer, only two sub-equalizers are independent and one output is optimized using the CMA. The second stage of the equalizer is an ordinary CMA equalizer where the four sub-equalizers are adjusted independently, optimizing both outputs simultaneously. The first stage is to compensate PMD and the second one to compensate PDL and residual CD. Without loss of generality, we assume the x output is optimized in the first stage, the four sub-equalizers are adjusted according to the stochastic gradient algorithm given by

$$H_{xx1} \to H_{xx1} - \mu \frac{\partial\left(\varepsilon_{x'}^2\right)}{\partial H_{xx1}},\ H_{xy1} \to H_{xy1} - \mu \frac{\partial\left(\varepsilon_{x'}^2\right)}{\partial H_{xy1}},\ H_{yx1} \to -H_{xy1}^*,\ H_{yy1} \to H_{xx1}^* \tag{1}$$

where $\varepsilon_{x'}^2 = 1 - \left|E_{\det}'^x\right|^2$, μ is the convergence parameter, and $E_{\det}'^x$ is the output field at the x port of the first stage equalizer. The setting of the first stage is similar to the initial tap setup in [5]. By putting this function into a separate stage, two benefits can be obtained. One is that the equalizer can run blindly and there is no need to distinguish the initial setup phase from the tracking phase. The other benefit is that it provides an effective way to monitor PMD and PDL.

Because of the relationship in Eq. (1), the transfer function H_1 of the first stage equalizer can be normalized to a unitary matrix, so that we can easily get the received field when only x-polarization signal is transmitted from $E_{\det}'^x$ and H_1 as

$$\begin{pmatrix} E_{rx}^{x}(f) \\ E_{rx}^{y}(f) \end{pmatrix} = T \begin{pmatrix} E_{tx}^{x}(f) \\ 0 \end{pmatrix} = H_1^{-1} \begin{pmatrix} E_{\det}^{\prime x}(f) \\ 0 \end{pmatrix} = \frac{1}{\left|H_{xx1}(f)\right|^2 + \left|H_{xy1}(f)\right|^2} \begin{pmatrix} H_{xx1}^{*}(f) & -H_{xy1}(f) \\ H_{xy1}^{*}(f) & H_{xx1}(f) \end{pmatrix} \begin{pmatrix} E_{\det}^{\prime x}(f) \\ 0 \end{pmatrix} \quad (2)$$

With this optical field information, the changes with frequency of the state of polarization (SOP) for the received signal can be calculated and the PMD information of the link can be obtained using the Poincaré Sphere method [8]. Fig. 2 illustrates an example of SOP variation over frequency caused by PMD on the Poincaré sphere, where $\vec{\Omega}$ is the PMD vector. Differential group delay (DGD) can be expressed as $\Delta\tau = \Delta\varphi / \Delta\omega$, where $\Delta\omega$ is the angular frequency change and $\Delta\varphi$ is the corresponding SOP angle change on the plane that is perpendicular to the PSP, as shown in Fig. 2. What can be easily monitored is $\Delta\tau_{\perp} = \Delta\alpha / \Delta\omega = \Delta\tau \sin\theta$, the PMD component that is perpendicular to the signal SOP and causes the distortion of a signal, where θ is the angle between the signal SOP and PSP. Although in principle $\Delta\varphi$ can be obtained by data fitting, it has large errors when the signal SOP approaches the principal state of polarization (PSP) of the link. But it is sufficient to obtain $\Delta\tau_{\perp}$, as it is the PMD component that causes signal distortions and it is directly related to system PMD. Statistically $\Delta\tau_{\perp}$ is Rayleigh distributed, and it is related to $\Delta\tau$ as $\langle\Delta\tau_{\perp}\rangle = \pi\langle\Delta\tau\rangle / 4$ [9].

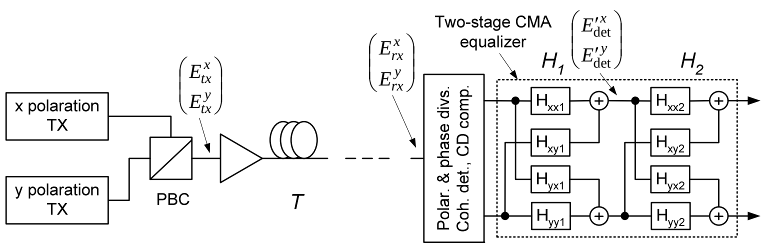

Fig. 1. PDM coherent communication system with the two-stage CMA equalizer.

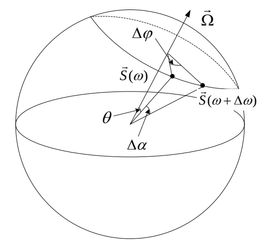
Fig. 2. Illustration of SOP variation over frequency on the Poincaré sphere.

PDL value can be estimated from transfer function of the second stage equalizer H_2. By calculating the output powers P_1, P_2, P_3, and P_4 with four input SOPs, S_1, $-S_1$, S_2 and S_3, at the equalizer's input, respectively, PDL value can be estimated as

$$PDL = 10 * \log10\left(T_{\max} / T_{\min}\right) \quad (3)$$

where $T_{\max} = m_{11} + \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}$, $T_{\max} = m_{11} - \sqrt{m_{12}^2 + m_{13}^2 + m_{14}^2}$, $m_{11} = 0.5(P_1 + P_2)$, $m_{12} = 0.5(P_1 - P_2)$, $m_{13} = P_3 - m_{11}$ and $m_{14} = P_4 - m_{11}$.

3. **Results**

The two-stage CMA equalizer technique was demonstrated by simulations and experiments for a 112-Gb/s PDM-QPSK modulated signal.

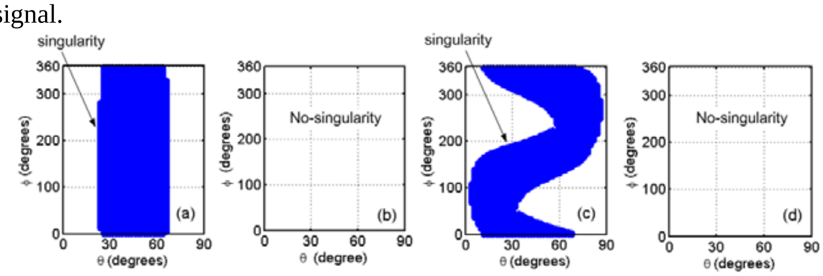

Fig. 3. Polarization demultiplexing results of simulations and experiments with different SOPs. In the simulation, 3 dB PDL was introduced in the system and in the experiment, the signal propagated 2400 km. Marked areas have the singularity problem. (a) simulation with the ordinary CMA, (b) simulation with the two-stage CMA, (c) experiment with the ordinary CMA, (d) experiment with the two-stage CMA.

a) Results on the singularity problem

A 112-G/s time-interleaved RZ-PDM-QPSK was used to test the singularity problem [10]. As pulses in x and y polarization are time-interleaved, they are more sensitive to the singularity problem. In simulation, after the transmitter, the polarization of the 112-Gb/s PDM-QPSK signal was changed by polarization controller with a Jones matrix T

$$T = \begin{pmatrix} \cos\theta & \sin\theta \cdot \exp(-i\phi) \\ -\sin\theta \cdot \exp(i\phi) & \cos\theta \end{pmatrix} \quad (8)$$

In the experiment, a 112-G/s time-interleaved RZ-PDM-QPSK signal propagated 2400 km in a Raman amplified system (the Raman system was the same as in [11]), and the captured data by a digital sampling scope was polarization rotated with the Jones matrix T before doing additional digital signal processing.

Figure 3 shows some results for both simulations and experiments. It shows that when an ordinary CMA equalizer is used, there is a large region in the space of SOP that has the singularity problem, but when the two-stage CMA equalizer is used, the singularity problem is completely avoided.

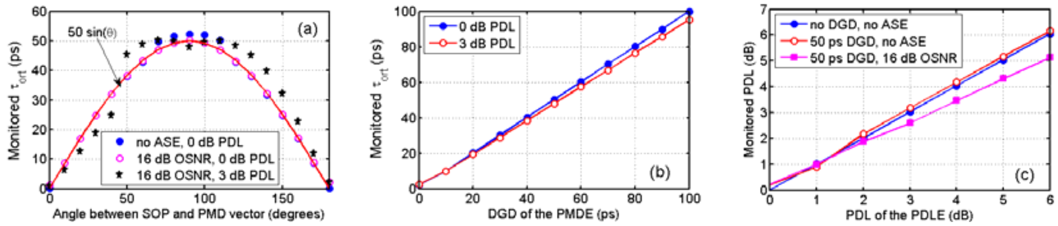

Fig. 4. (a) Monitored DGD versus the angle between the signal SOP and PSP with different noise and PDL values, DGD of the PMDE is 50 ps .(b) Monitored DGD versus the DGD of the PMDE with different PDL values. The signal SOP is perpendicular to the PMD vector, (c) Monitored PDL versus the PDL of the PDLE. The signal SOP is perpendicular to the PMD vector.

b) Results on PMD and PDL monitoring

In this study, a 1st-order PMD emulator (PMDE) and a PDL emulator (PDLE) were used between the 112-Gb/s PDM-QPSK transmitter and receiver, and a polarization controller was inserted before the PMDE to change the angle between the signal SOP and PSP of the PMDE. Amplified spontaneous emission (ASE) noise was loaded at the receiver to change the optical signal to noise ratio (OSNR) to investigate the noise impact on the monitoring technique. Simulation results on PMD and PDL monitoring are given in Fig. 4. Fig. 4 (a) and (b) shows that monitored DGD is the PMD component perpendicular to SOP of the signal, and that ASE noise and PDL in the system have little effect on the accuracy of the PMD monitoring technique. The PDL monitoring result with one SOP is given in Fig. 4 (c) and the results for other SOPs is not very different. It shows that the technique can estimate PDL accurately, and it is not affected by PMD. ASE noise induces some degradations to the PDL monitoring technique. This is because that PDL causes different attenuations for noise and signal and CMA tries to get equal amplitude in the two outputs of the equalizer. This induces artificial PDL in the equalizer. With a proper OSNR required by the system, the monitoring error is moderate.

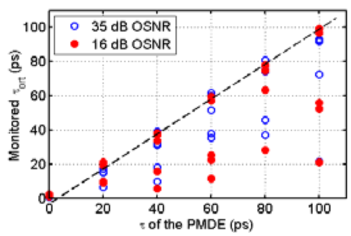

Fig. 5. Experiment result of PMD monitoring. 5 different SOPs for each DGD value

In the experiment, only a PMDE was used. The result is shown in Fig. 5, where 5 samples for different launch SOPs were taken for each DGD value of the PMDE, and the results of two different OSNR values were measured. Fig. 5 shows that the monitored DGD values change with different SOPs (as the monitored value is the PMD component perpendicular to the signal SOP, as discussed before). The largest DGD value that is monitored is close to the DGD value of the PMDE. The results are consistent with theory.

4. Conclusion

We have proposed and demonstrated a two-stage CMA equalizer, which not only eliminates the singularity problem in a traditional CMA equalizer, but provides an effective way to estimate PMD and PDL of the channel. The results of both simulations and experiments are presented.

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