A Modulation-Format-Transparent Monitoring Scheme for Receiver Impairments under CD Effect

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***Abstract*—We propose a receiver impairment monitoring scheme under chromatic dispersion. Simulation results show that our proposed algorithm is modulation-format-transparent and has a wider monitoring range than 4×2 MIMO based on the radius-directed equalization algorithm.**

Keywords*—*Rx impairments monitor, chromatic dispersion, modulation-format-transparent.

I. Introduction

The increasing demand for optical communication bandwidth is driven continually by the rapid growth of global Internet traffic. To improve spectral efficiency, higher baud rates and higher-order modulation formats have become an inevitable trend in coherent optical communications. However, high-order modulation formats and high baud-rate systems are more sensitive to receiver impairments such as in-phase/quadrature (IQ) amplitude imbalance, phase imbalance, and skew. In addition, chromatic dispersion (CD) from the fiber link will cause an IQ mixing effect[1], and the mutual coupling with receiver impairments will cause severe system performance degradation. Therefore, it's critical to monitor receiver impairments under link chromatic dispersion.

Recently, various schemes have been proposed to compensate for and monitor CD and Rx impairments [2–7]. For an adaptive filter, 4×2 MIMO based on the radius-directed equalization algorithm (RDE) and independent dispersion compensation method are used to compensate for CD and Rx impairment monitoring[2]. The disadvantage is that the radius decision should be set with a known format. Multi-layer (ML) filters based on a backpropagation stochastic-gradient-descent (SGD) method [3] can be used to simultaneously compensate transceiver impairments in long-haul optical communication systems with large accumulated CD. The tap coefficients based on the convergence of the wide linear (WL) filter [4] can also be used to monitor the Rx IQ skew. Still, as far as we know, the above schemes are not directly applicable to different modulation formats. The scanning method [5] based on the clock tone (CTS) can monitor and estimate CD for the cascaded DSP algorithm scheme. The elliptic correction method or GSOP algorithm[6] can be used to monitor and estimate Rx IQ amplitude and phase imbalance. The Godard timing error detection method (Godard-TED)[7] can be used to monitor the Rx IQ skew. However, it is common sense that the two impairments of CD and Rx skew will be coupled. The Godard-TED algorithm will suffer severe performance degradation when the above two impairments are presented simultaneously, leading to the failure of IQ skew estimation.

In this work, we propose a modified Godard-TED algorithm with CD robustness to monitor skew. Furthermore, a cascaded DSP algorithm with modulation format transparency is proposed to monitor all Rx impairments in the presence of CD.

II. Model and Principle

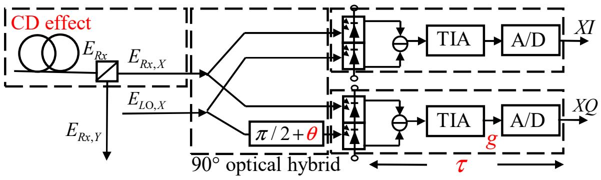

Fig.1 Structure of a coherent Rx with IQ imperfections

We take X polarization as an example. Fig.1 shows the structure of a coherent receiver with IQ imperfections. The damage matrix based on the IQ signal is expressed in the frequency domain as shown in Eq.(1). In this paper, IQ amplitude imbalance is $g[dB]$. IQ phase imbalance is $\theta[\deg]$. IQ skew is $\tau[ps]$.

$$\begin{bmatrix} I^{'}(\omega) \\ Q^{'}(\omega) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -g\sin\theta e^{j\omega\tau} & g\cos\theta e^{j\omega\tau} \end{bmatrix} \begin{bmatrix} I(\omega) \\ Q(\omega) \end{bmatrix} \tag{1}$$

In fact, the effect of CD is added to the signal before the receiver. Eq.(2) represents the CD frequency domain function, the dispersion coefficient is β_2. The length of the optical fiber link is L. We first discuss the interaction between CD and IQ imbalance. Because CD only causes signal pulse broadening, it does not affect the power and orthogonality of the received signal, so it will not affect the monitoring of receiver IQ amplitude and phase imbalance. Similarly, the amplitude and phase imbalances are linear transformation processes in the time domain and will not cause pulse broadening, so they will not affect the monitoring of dispersion.

$$H_{CD}(\omega) = \exp(j\beta_2 L\omega^2/2) \tag{2}$$

Next, we will further discuss the interaction between CD and IQ skew. We consider the situation that only CD and IQ skew exist to simplify the problem, as shown in Eq.(3). $h_{CD}(t) = h_{cd,I}(t) + jh_{cd,Q}(t)$ is the inverse Fourier Transform of $H_{CD}(\omega)$. $\hat{I}(t)$ is the *I*-channel signal and $\hat{Q}(t)$ is the *Q*-channel signal with the above impairments. Although in the frequency domain, we can avoid convolution operations like in the time domain, it is still difficult to directly extract helpful information due to the limitations of the IQ basis. We use the widely linear (WL) model [8] to analyze the principle. Eq.(4) could be derived from Eq.(3). That is, the signal itself and the conjugate term are used as the basis to clarify the influence of IQ skew and CD on the signal. Combine IQ signals into complex signals $s(t) = I(t) + jQ(t)$. According to the Fourier transform relation $F\{s^*(t)\} = S^*(-\omega)$, the complex signal is $\hat{S}(\omega)$ after adding the above two damages. Coefficients are shown in Eq.(5).

$$\begin{bmatrix} \hat{I}(t) \\ \hat{Q}(t) \end{bmatrix} = \begin{bmatrix} 1 & \\ & \delta(t-\tau) \end{bmatrix} \otimes \begin{bmatrix} h_{cd,I} & -h_{cd,Q} \\ h_{cd,Q} & h_{cd,I} \end{bmatrix} \otimes \begin{bmatrix} I(t) \\ Q(t) \end{bmatrix} \tag{3}$$

$$\hat{S}(\omega)=C_1S(\omega)+C_2S^*(-\omega) \tag{4}$$

where

$$C_1=H_{CD}(\omega)(1+e^{-j\omega\tau})/2$$
$$C_2=H^*_{CD}(-\omega)(1-e^{-j\omega\tau})/2 \tag{5}$$

Eq.(6) shows that the traditional zero-forcing CD compensation will fail because it cannot compensate for the dispersion conjugate term caused by the existence of IQ skew.

$$\hat{S}_{ZF}(\omega)=H^{-1}_{CD}(\omega)\hat{S}(\omega) \tag{6}$$

According to Eq.(2), $H^*_{CD}(-\omega)=H^{-1}_{CD}(\omega)$. After traditional CD compensation, the CD frequency domain conjugate term will become the original square term $\left(H^{-1}_{CD}(\omega)\right)^2$.

By the above analysis, the optimal compensation strategy should be reverse damage compensation according to the order of damage introduction. IQ skew is compensated first, and then the dispersion is compensated. Considering that Eq.(2) will cause a quadratic phase change on the entire signal spectrum, causing the neighboring frequency components in the clock signal to experience several 2π cycles, thus linearly changing the phase relationship of them in the clock signal. The traditional Godard-TED algorithm fails to estimate the skew under dispersion. Therefore, extracting the CD interference term in the clock signal is vital. We propose a CD-robust modified Godard-TED algorithm that can be used to estimate IQ skew. This scheme enhances the tolerance of CD by introducing the CD interference term in the traditional Godard-TED. In DSP, $S(n)$ is the signal after experiencing CD. $S(n)S^*(n+N/2)$ can be separated by CD interference term $\exp(j\psi f_s^2 n/N)$, where $\psi=\beta_2 L/2$, f_s is the sampling frequency, N is the number of samples. From this, we can obtain the modified Godard-TED algorithm, and the timing error of each branch of the received signal can be expressed as shown in Eq.(7). Estimated value of skew τ is shown in Eq.(8).

$$t_m=\arg\Big(\sum_{n=0}^{N/2-1}S_m(n)S^*_m(n+N/2)\exp(-j\psi f_s^2 n/N)\Big)/2\pi f_s$$
$$m\in\{XI,XQ\} \tag{7}$$

$$\tau=t_{XQ}-t_{XI} \tag{8}$$

Finally, a complete CD and Rx impairment monitoring scheme is proposed, as shown in Fig. 2. First, the CD is monitored based on CTS, and substitute the estimated CD value into the modified Godard-TED algorithm to monitor and compensate for IQ skew. Then use the GSOP[6] algorithm to monitor and compensate for IQ amplitude and phase imbalance. Finally, CD compensation is performed.

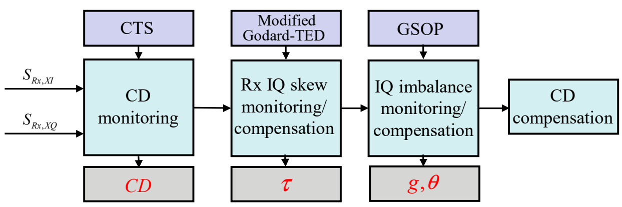

Fig. 2 Cascaded DSP Algorithm for Monitoring

III. RESULTS AND DISCUSSION

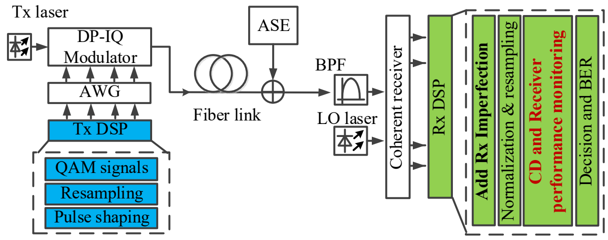

Fig.3 System diagram of CD and receiver performance monitoring

To verify the effectiveness of our proposed method, a dual-polarization 28Gbaud 16QAM system is numerically investigated. The system diagram is shown in Fig.3. For all of the simulated cases, the system transmission uses 2^{15} symbols, the OSNR is set to 24dB, the root raised cosine (RRC) filter is used to achieve pulse shaping, the roll-off factor is set to 1, the fiber link length is 80km, and the CD coefficient is 17ps/nm/km. After the signal is generated at the transmitter side, the CD is added through the optical fiber link, and Rx DSP adds Rx impairments. The impairment estimation results are obtained from the average of 10 independent trials.

We first analyze the impact of Rx IQ impairments on CD monitoring. As shown in Fig.4, the simulation results show that for the cumulative CD in the range of [0,1700]ps/nm, three different Rx IQ impairments at 10ps IQ skew, 3dB IQ amplitude imbalance, and 10deg IQ phase imbalance. In the case of CD, the monitoring error of CD is less than 1ps/nm. It proves that this scheme is not sensitive to Rx impairments.

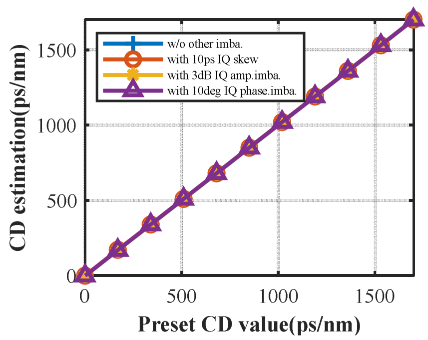

Fig. 4 Effects of different Rx IQ impairments on CD monitoring

The impact of CD on the IQ impairment of the receiver is discussed. As shown in Fig. 5, at CD=1360ps/nm scenario (accumulated CD value of 80km), each simulation only adds one Rx impairment (-15~15ps IQ skew, -5~5dB IQ amplitude imbalance, -10~10deg IQ phase imbalance). Among them, the blue plus sign indicates the actual value of the added IQ impairment, and the signs of other colors indicate three different signal modulation formats of QPSK, 16QAM, and 64QAM. The maximum monitoring error of IQ skew is 0.03ps. IQ imbalance monitoring error is 0.1dB and 0.2deg, respectively. The simulation results show that all the IQ impairment estimation has excellent accuracy. It proves that the Rx impairment monitoring scheme is not affected by CD and has acceptable monitoring performance for different modulation signal formats. Therefore, the cascaded DSP algorithm proposed in this paper is an Rx impairment monitoring scheme with CD robustness and signal modulation format transparency.

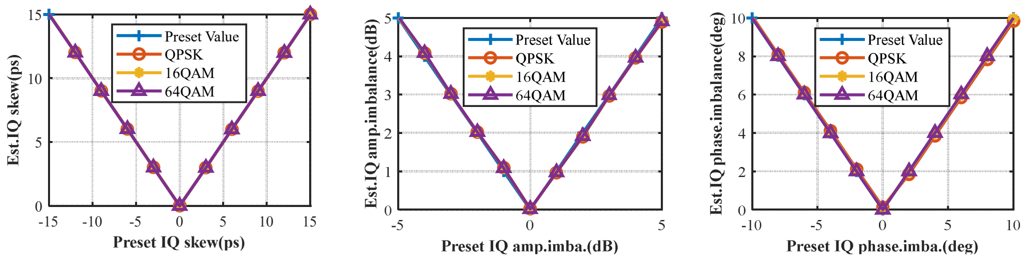

Fig. 5 The Rx.IQ impairment monitoring performance of signals with different modulation formats at CD=1360ps/nm.

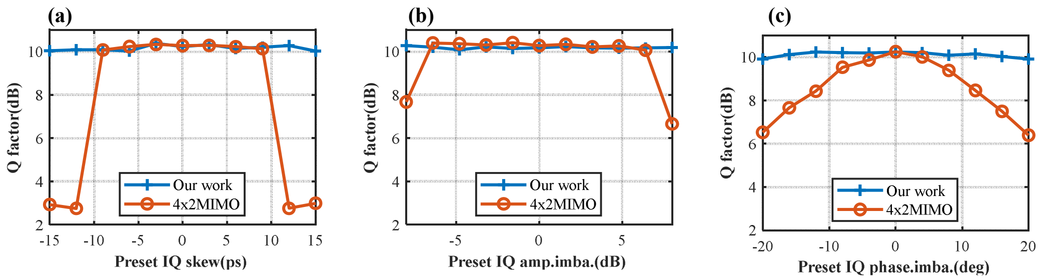

Fig. 6 Q factor performance comparison of two schemes under different Rx.IQ impairment conditions

Finally, we compare our scheme with the 4×2 MIMO receiver monitoring scheme based on independent CD compensation in [2]. We choose the Q factor as a metric for the performance comparison. In order to compare monitoring performance between the two schemes fairly, we adjust the parameters of the 4×2 MIMO to the optimum (taps=15, step=1e-3, iteration=10) to keep the Q factor of the two schemes in good agreement when the coherent receiver system has no Rx. IQ impairments. As shown in Fig. 6, in the CD=1360ps/nm, only one kind of impairment is added per simulation (-15~15ps IQ skew, -8~8dB IQ amplitude imbalance, -20~20deg IQ phase imbalance). The blue plus sign indicates our work, and the orange circle indicates 4×2 MIMO. Fig.6(a) points out that when the IQ skew is above 10ps, the Q factor of the 4×2 MIMO drops significantly. The reason is that it tends to fail to converge in the large skew scenario, which leads to the deterioration of skew monitoring performance. Fig.6(b) and Fig.6(c) show that the Q factor of 4×2 MIMO is gradually degraded. The reason is that the initial steps are less tolerant of significant IQ imbalances resulting in larger monitoring errors. One possible solution is precisely optimizing the MIMO parameters. More than adding more taps of MIMO will be needed to solve this problem. The optimal convergence step size also needs to match. For example, when the number of taps is enough, we must traverse the step and select the best convergence step size for different receiver impairments. However, it will inevitably reduce the MIMO-based scheme's flexibility. The accuracy of our scheme depends on the statistical value of the signal, there is no convergence problem, and as long as the sampling points are sufficient, it is not sensitive to outliers.

In addition, the MIMO based on the RDE algorithm is dependent on the modulation format. Specifically, in the radius decision mode, the thresholds can be set with the already-known formats. Besides, the optimal step size of the MIMO also depends on the modulation formats. Therefore, the MIMO-based monitoring scheme is not flexible enough to meet the requirement under a dynamic optical network.

IV. Conclusion

In this work, we propose an Rx impairment monitoring scheme in the presence of CD. The scheme includes CTS, modified Godard-TED, and GSOP in our cascaded manner. IQ imbalances do not influence CD monitoring based CTS, and a modified Godard-TED algorithm taking into account CD could be used to monitor IQ skew. The monitoring accuracy of Rx impairments is 0.03ps, 0.1dB, and 0.2deg, respectively. Simulation results show that our scheme is applicable to multiple modulation formats and has a better Q factor than the 4×2 MIMO based-scheme in the scenario of significant IQ impairments.

Acknowledgment

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