A Novel Low Complexity and Precise Transceiver IQ skew Calibration Method for Single Carrier Coherent System

Wei Wang[1,2], Zhenpeng Wu[1,2], Dongdong Zou[1,2], Fan Li[1,2,*], and Zhaohui Li[1,2]
[1]School of Electronics and Information Technology, Guangdong Provincial Key Laboratory of Optoelectronic Information Processing Chips and Systems, Sun Yat-Sen University, Guangzhou 510275, China
[2]Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, China
Email: lifan39@mail.sysu.edu.cn

Abstract: We propose a novel precise transceiver IQ skew calibration method utilizing the specially designed training signal for single carrier coherent system. The results show that the estimation error can be within ±0.2ps. © 2024 The Author(s)

1. Introduction

Coherent system has been gradually extended to short-reach scenarios to meet the increasing demands of large-capacity for datacenter interconnects (DCI). And employing the signal with high baud-rate or high-order modulation format is a straightforward way to achieve an increase in transmission capacity. However, as the baud-rate or modulation order increases, the performance degradation caused by transceiver in-phase and quadrature (IQ) skew will gradually become prominent [1]. To address this issue, quite a number of advanced digital signal processing (DSP) algorithms have been proposed for IQ skew adaptive equalization or precise calibration [2-7].

Multiple-input and multiple-output (MIMO) equalizer is a common solution to compensate for transceiver IQ skew adaptively [2, 3]. However, due to the crosstalk between I and Q tributaries at the receiver as well as the addition of the other impairments, the compensation for the Tx-skew and Rx-skew needs to be separated. As a result, the computational complexity increases, which is unacceptable for the cost and power consumption sensitive DCI applications. Under the consideration of the accuracy and low-complexity of the DSP algorithms, precise calibration techniques are preferred. Up to now, several calibration methods based on specially designed signals or specific system architecture have been reported. However, a considerable portion of these methods can only estimate Tx-skew or Rx-skew individually, so that the measurements of Tx-skew and Rx-skew should be conducted separately [4-6]. The operation process will become much simpler if Tx-skew and Rx-skew can be estimated simultaneously.

In this paper, a novel low complexity and precise transceiver IQ skew calibration method based on specially designed training signal is proposed, which can simultaneously estimate Tx-skew and Rx-skew in one measurement. Generally, IQ crosstalk results in a mixture of Tx-skew and Rx-skew, making the measurement difficult. In the proposed method, the signal is transmitted individually in I and Q channels at different time periods, so that the IQ skew introduced at the transmitter and receiver can be separated. Besides, the specially designed signal exhibits the characteristic of being composed of four identical blocks in the frequency domain. And the transceiver IQ skew can be calculated through the correlation operations between these frequency blocks. The experimental results indicate that the estimation error of the proposed method is less than ±0.2ps. After calibration based on the estimated skew values, about 2dB OSNR improvement can be observed with 1ps skew at the transceiver for dual-polarization (DP) 50Gbaud 16QAM signal in OBTB and 80km SMF transmission, and shows the similar performance to that utilizing Godard phase detector (GPD) and 4×4 MIMO equalizer but in a low complexity manner.

2. Operation Principle

Figure 1(a) gives the structure of the specially designed training signal. To achieve the simultaneous estimation of the transceiver IQ skew through one measurement without the influence of IQ crosstalk, the training signal should be transmitted individually in I and Q channels at different time periods. For simplicity, the principle is introduced in single-polarization system. As shown in Fig. 1(a), the first half of the training sequence s^I is set to be real, while the second half of the sequence s^Q is set to be imaginary. And the signals with Tx-skew are denoted as s_{Tx}^I and s_{Tx}^Q. Since the time delay in time domain reflects as phase shift in frequency domain, the real and imaginary parts of the received signal with Rx-skew for s_{Tx}^I can be represented as $S_{Rx-I}^I(k)=\left(S_{Tx}^I(k-k_1)+S_{Tx}^I(k+k_1)\right)e^{j\phi_{Rx}^I k}/2$ and $S_{Rx-Q}^I(k)=j\left(S_{Tx}^I(k+k_1)-S_{Tx}^I(k-k_1)\right)e^{j\phi_{Rx}^Q k}/2$, where k_1 is the frequency offset. ϕ_{Rx}^I and ϕ_{Rx}^Q can be written as $\phi_{Rx}^I=-2\pi\tau_{Rx}^I/N$ and $\phi_{Rx}^Q=-2\pi\tau_{Rx}^Q/N$ respectively, where τ_{Rx}^I and τ_{Rx}^Q are the time delay in I and Q channels at the receiver, and N is the FFT size. To calculate the skew values, the signal is designed to exhibit the feature of being composed of four identical blocks in the frequency domain as shown in Fig. 1(a). By performing correlation operation between adjacent frequency blocks of $S^I_{Rx-I}(k)$, we can obtain:

$$\begin{aligned} CrrS^I_{Rx-I} &= \sum S^I_{Rx-I}(k)\cdot S^{I*}_{Rx-I}(k+N_d) \\ &\approx \sum \frac{1}{4}e^{-j\phi^I_{Rx}N_d}\cdot\left[S^I(k-k_1)\cdot S^I(k-k_1+N_d)\cdot e^{-j\phi^I_{Tx}N_d}+S^I(k+k_1)\cdot S^I(k+k_1+N_d)\cdot e^{-j\phi^I_{Tx}N_d}\right] \end{aligned} \tag{1}$$

where N_d is the size of each block. ϕ^I_{Tx} can be expanded as $\phi^I_{Tx}=-2\pi\tau^I_{Tx}/N$, where τ^I_{Tx} is the time delay in I channel at the transmitter. Taking the angle of $CrrS^I_{Rx-I}$, we have can obtain $angle\left(CrrS^I_{Rx-I}\right)=-(\phi^I_{Tx}+\phi^I_{Rx})N_d$. Similarly, $CrrS^I_{Rx-Q}$ can be calculated by the correlation operation of $S^I_{Rx-Q}(k)$, so that $angle\left(CrrS^I_{Rx-Q}\right)=-(\phi^I_{Tx}+\phi^Q_{Rx})N_d$. Obviously, Rx-skew is obtained by:

$$\tau^Q_{Rx}-\tau^I_{Rx}=\frac{N}{2\pi N_d}\left[angle\left(CrrS^I_{Rx-Q}\right)-angle\left(CrrS^I_{Rx-I}\right)\right] \tag{2}$$

By utilizing the second half of the sequence s^Q, the Tx-skew can be calculated in the same way:

$$\tau^Q_{Tx}-\tau^I_{Tx}=\frac{N}{2\pi N_d}\left[angle\left(CrrS^Q_{Rx-I}\right)-angle\left(CrrS^I_{Rx-I}\right)\right] \tag{3}$$

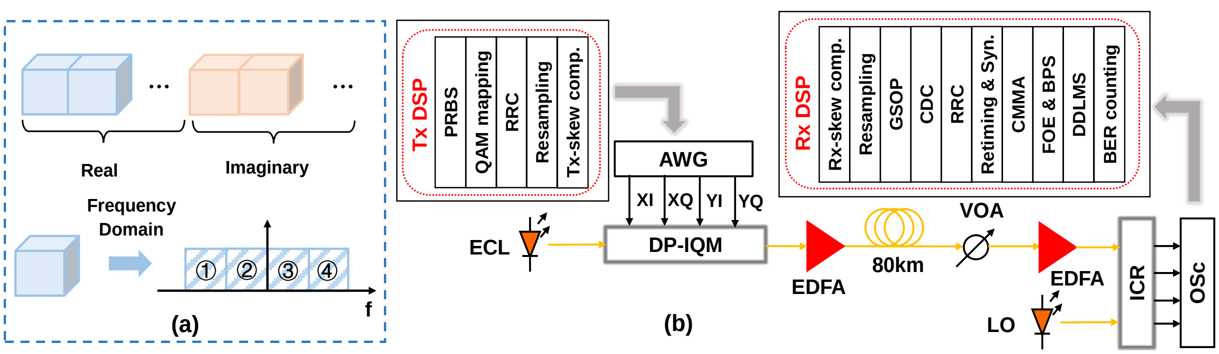

Fig. 1. (a) Structure of the training signal. (b) Experimental setup and DSP flow.

3. Experimental setup and results

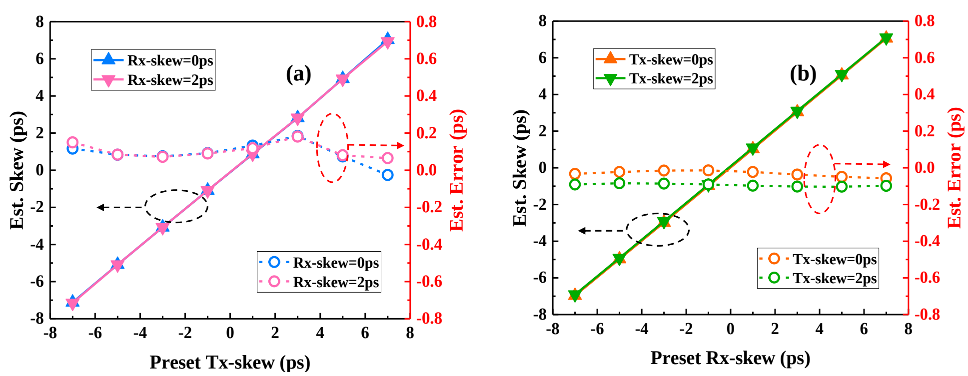

Fig. 2. (a) Estimated Tx-skew and error versus preset Tx-skew. (b) Estimated Rx-skew and error versus preset Rx-skew.

Figure 1(b) shows the experimental setup, together with the corresponding DSP flow. At the transmitter, an arbitrary waveform generator (AWG) working at 64GSa/s sampling rate is used to provide electrical driving signals to the DP IQ modulator (DP-IQM). And the optical carrier is provided by an external cavity laser (ECL) with output power of 16dBm and linewidth less than 100kHz. The modulated signal is boosted by an Erbium-doped fiber amplifier (EDFA), and then injected into 80km SMF. To adjust the system OSNR, a variable optical attenuator (VOA) is used in conjunction with another EDFA. At the receiver, the received signal and local oscillator (LO) laser are connected to a finisar 40-G class integrated coherent receiver (ICR) for coherent reception. Then, the detected signals are captured by a Lecory oscilloscope (Osc) with 80GSa/s sampling rate. In the calibration phase, the specially designed training signal is first transmitted. At the receiver, the transceiver IQ skew values are calculated just after resampling and synchronization. Based on the estimated skew values, the Tx-skew and Rx-skew can be compensated when transmitting data. In the experimental, the performance of 50Gbaud DP-16/32QAM signal is investigated.

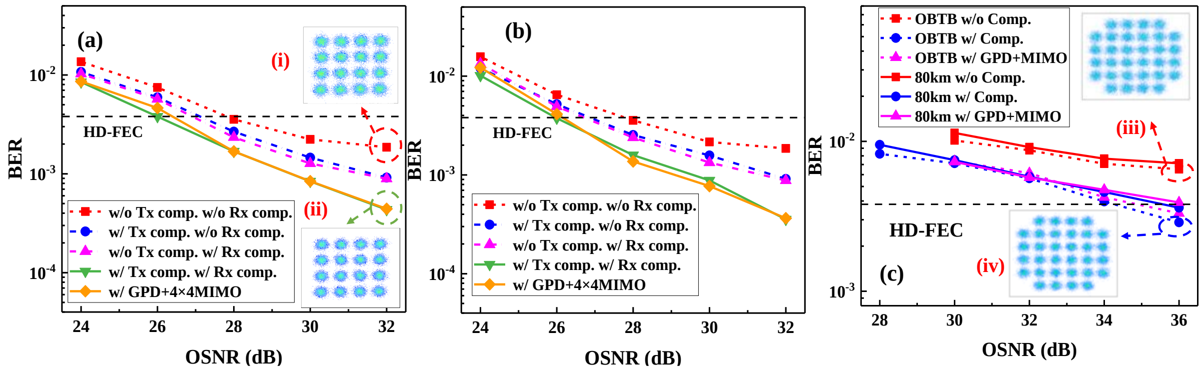

Fig. 3. BER versus OSNR of 50Gbaud DP-16QAM in (a) OBTB and (b) 80km SMF transmission, and (c) 50Gbaud DP-32QAM.

To evaluate the estimation accuracy of the proposed algorithm, the transceiver skew in our experimental system is first calibrated to ~0ps. Then, Tx-skew and Rx-skew are added artificially at the transceiver. Fig. 2(a) gives the estimated Tx-skew and the corresponding estimation error versus preset Tx-skew with 0/2ps Rx-skew. The results show that the estimation error of Tx-skew can be within ±0.2ps. Similarly, the Rx-skew is also measured under different preset Rx-skew with 0/2ps Tx-skew as shown in Fig. 2(b), and the estimation error is also less than ±0.2ps. Fig. 3(a) shows the BER versus OSNR of 50Gbaud DP-16QAM signal in OBTB transmission with 1ps preset Tx-skew and Rx-skew. About 2dB OSNR improvement can be observed at the HD-FEC threshold after skew calibration, while 1dB OSNR improvement is obtained with only Tx-skew or Rx-skew compensation. The performance is also compared to that utilizing GPD and 4×4 MIMO equalizer, similar performance is achieved while the proposed method operates in a lower complexity manner. The constellations of signals without and with skew compensation at 32dB OSNR are given in Fig. 3(a) as insets (i) and (ii). The BER of 50Gbaud DP-16QAM signal after 80km SMF transmission is also measured, and the results are plotted in Fig. 3(b). The performance is similar to that of OBTB, and about 2dB OSNR improvement can be obtained at the HD-FEC threshold after skew calibration. Fig. 3(c) gives the BER performance of 50Gbaud DP-32QAM signal, the results show that the BER can be below the HD-FEC threshold both in OBTB and 80km SMF transmission after transceiver IQ skew calibration at 36dB OSNR. And the constellation of the signal after skew calibration with the proposed method is clearer than that without skew compensation.

4. Conclusion

A novel low complexity and precise IQ skew calibration method utilizing specially designed training signal is proposed in this work, which can achieve the simultaneous estimation of the transceiver IQ skew. The experimental results show that the measurement error of the proposed algorithm can be less than ±0.2ps. Besides, about 2dB OSNR improvement can be obtained after transceiver skew calibration for 50Gbaud DP-16QAM signal, and the performance is similar to that with GPD and 4×4 MIMO equalizer.

5. Acknowledge

This work is partly supported by the National Key Research and Development Program of China (2021YFB2900900); Guangdong Basic and Applied Basic Research Foundation (2023B1515020003); National Natural Science Foundation of China (62271517); Open Fund of IPOC (BUPT) (IPOC2020A010).

6. References

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