Fast Phase Retrieval and IQ Impairments Compensation of Twin-SSB Signal in Direct Detection System

Xiuquan Cui[1] , Yanfu Yang[1,*] , Jianyu Wang[1] , Linsheng Fan[1] , Qi Wu[2]
[1]Department of Electronic and Information Engineering, Harbin Institute of Technology, Shenzhen 518055, China
[2]State Key Lab of Advanced Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
e-mail: yangyanfu@hit.edu.cn

***Abstract*—We propose a modified carrier-assisted phase retrieval (MCCA-PR) scheme based on Gerchberg-Saxton (GS) algorithm to reconstruct a twin-SSB signal fast, then compensate the transmitter IQ impairments with a widely linear (WL) equalizer.**

Keywords—Gerchberg-Saxton algorithm, direct detection, IQ impairments, Twin-SSB signal, widely linear equalizer

I. Introduction

Compared with coherent detection, direct detection(DD) is more prevalent in data center interconnects(DCIs) due to its simple structure and low cost, especially in inter-DCI scenarios over 80km. To reconstruct the optical field, some advanced self-coherent detection schemes for double-sideband (DSB) signal are proposed, including Carrier-assisted differential detection (CADD)[1] and Asymmetric self-coherent detection (ASCD)[2]. However, these schemes require a strong carrier, resulting in an excessively large carrier-to-signal power ratio (CSPR). The field reconstruction scheme without carrier based on the Gerchberg-Saxton (GS) algorithm only uses two PDs and one dispersive element to reconstruct the optical field from the measured intensity[3]. However, digital backpropagation (DBP) and phase updates are performed at the transmitter during the iterative process, the number of iterations is high (thousands), and 20% of the pilot symbols are required, resulting in high redundancy and computational complexity. Previously, a central carrier-assisted phase-retrieval (CCA-PR) scheme is proposed to reduce the phase ambiguity in the GS algorithm by using a central direct current (DC) carrier approach, reducing the number of iterations to 20, which requires only 1 dB CSPR[4].

Due to the usage of a twin-SSB signal in CCA-PR scheme, when using an IQ modulator to implement complex signal electro-to-optical (E/O) conversion, IQ impairments at the transmitter side, including skew, amplitude imbalance, and phase imbalance, can severely affect the system performance. In the coherent optical system, the multiple-input multiple-output (MIMO) equalizer is a common scheme to equalize the above impairments[5]. The widely linear (WL) equalizer utilizes signal and conjugation of the signal to compensate for the impairments, and its performance is superior than MIMO[6].

In this paper, we propose a receiver DSP scheme combining fast field retrieval and transmitter impairments compensation in the direct detection system. Firstly, the modified carrier-assisted phase retrieval (MCCA-PR) scheme improves convergence speed and algorithm performance by introducing amplitude error in the intensity constraint to match the incompatibility between amplitude and phase in the previous iterations. Then the transmitter IQ impairments and interference between the two baseband signals are compensated with a WL equalizer. We conduct numerical simulations for 30Gbaud twin-SSB 16QAM signal transmission over 80km SSMF. In the case of 2ps IQ skew, 2dB amplitude imbalance, and 20deg phase imbalance, only requires less than 1dB OSNR penalty at the 7% HD-FEC limit, compared with no transmitter IQ impairments signal.

II. Principle

A. MCCA-PR

The MCCA-PR scheme is shown in Fig. 1(c). Before the first iteration, the initial phase $\angle a(t)$ and the amplitude error $aerr$ is set to 0. $a(t)$ is convolved with the dispersion element propagation function $h_D(t)$ to obtain $b(t)$. Unlike the CCA-PR scheme, the MCCA-PR scheme introduces an amplitude error in intensity constraint, that is, $berr = \mathrm{abs}(b(t)) - \sqrt{I_b(t)}$, to match the mismatch between the amplitude and phase in the previous iterations. $h_{BW}(t)$ is a dual bandpass filter that constrains the signal spectrum. The reconstructed field $b(t)$ and the reverse transfer function $h_D^{-1}(t)$ convolution to obtain $a(t)$, then the amplitude error $aerr = \mathrm{abs}(a(t)) - \sqrt{I_a(t)}$ is introduced in intensity constraint, and a complete iterative process ends. The symbol-wise absolute phase error $\Delta\theta(t)$ describes the convergence of the iterations, denoted as:

$$\Delta\theta(t) = |\angle(T_x S(t) \cdot R_x^* S(t))| \tag{1}$$

Where $T_x S(t)$ is the transmitted QAM symbol, and $R_x S(t)$ is the reconstructed QAM symbol.

B. IQ impairments and WL equalizer

Due to a singularity at 0 GHz in the complex-valued DSB self-coherent detection scheme, we analyze transmitter IQ impairments' effect on twin-SSB QAM signals. After up-conversion, two independent baseband QAM signals are converted into left-band and right-band signal respectively.

$$\begin{aligned} S_L(t) &= I_L(t) + jQ_L(t) \\ S_R(t) &= I_R(t) + jQ_R(t) \end{aligned} \tag{2}$$

then $S_L(t)$ and $S_R(t)$ are synthesized into a twin-SSB QAM signal $S(t) = I(t) + jQ(t)$, where

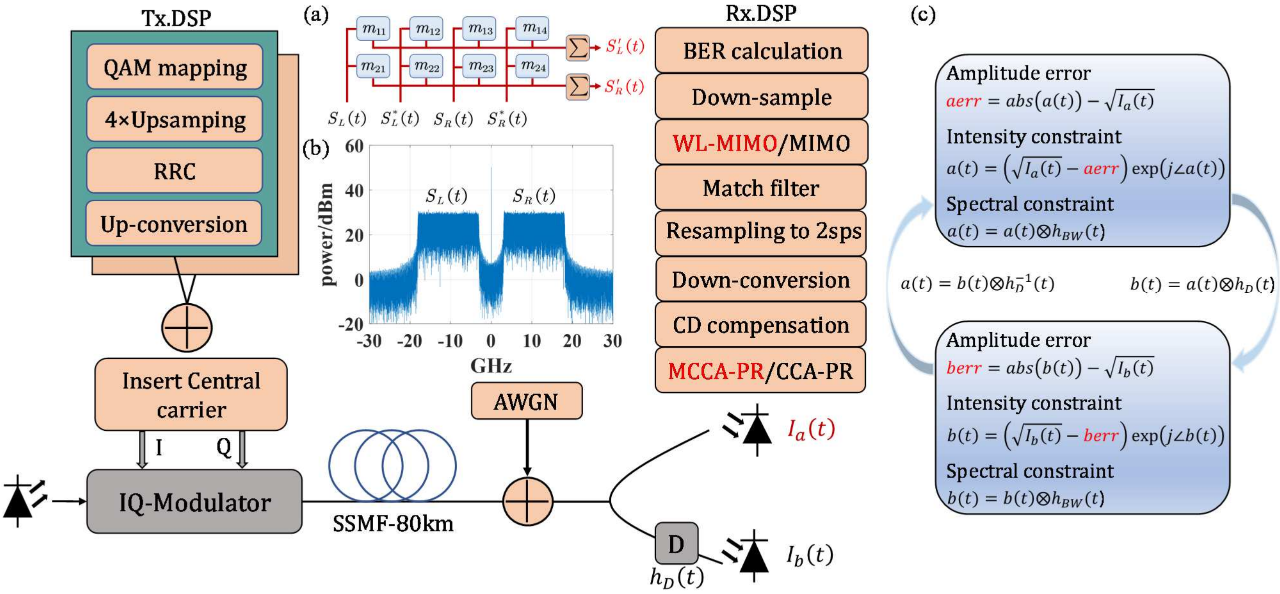

Fig.1 Simulation setup and DSP stack. (a) Structure of WL-MIMO. (b) Transmitter signal spectrum. (c) MCCA-PR flow chart.

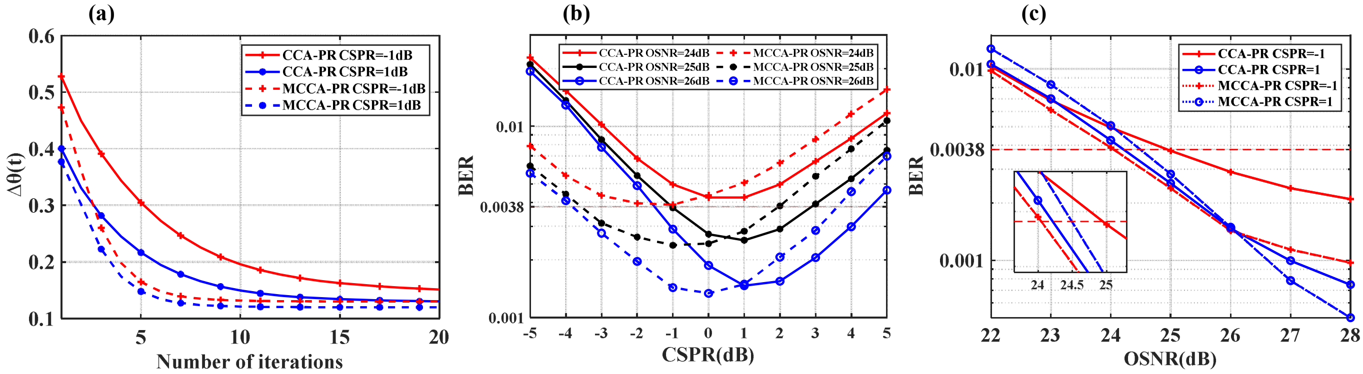

Fig.2 (a) $\Delta\theta(t)$ versus the number of iterations. (b) BERs versus CSPR under different OSNRs. (c) BERs versus OSNR under different CSPRs.

$$\begin{aligned} I(t) &= I_L(t) + I_R(t) \\ Q(t) &= Q_L(t) + Q_R(t) \end{aligned} \tag{3}$$

With transmitter IQ impairments, the generated optical signal can be expressed as[7]

$$\begin{aligned} \begin{bmatrix} I'(t) \\ Q'(t) \end{bmatrix} &= \begin{bmatrix} 1 & -g\sin(\theta) \\ 0 & g\cos(\theta) \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \delta(t-\tau) \end{bmatrix} \otimes \begin{bmatrix} I(t) \\ Q(t) \end{bmatrix} \\ &= \begin{bmatrix} 1 & -g\sin(\theta)\delta(t-\tau) \\ 0 & g\cos(\theta)\delta(t-\tau) \end{bmatrix} \otimes \begin{bmatrix} I_L(t) + I_R(t) \\ Q_L(t) + Q_R(t) \end{bmatrix} \end{aligned} \tag{4}$$

Where g is amplitude imbalance, θ is phase imbalance and τ is IQ skew. After up-conversion and the introduce of the IQ impairments, $[I_L(t), I_R(t), Q_L(t), Q_R(t)]$ are aliased, which will cause interference between the two baseband signals. As a result, the transmitter signal will contain IQ impairments and related interference. Due to the inherent imitations, the MIMO equalizer cannot compensate for the aforementioned impairments. The structure of the WL equalizer, as shown in Fig.1(a), $[S_L(t), S_L^*(t), S_R(t), S_R^*(t)]$ are four complex-valued inputs and $[S'_L(t), S'_R(t)]$ are two outputs, so it can also be considered as a WL-MIMO.

III. SIMULATION SETUP AND RESULT

We conduct a twin-SSB 30Gbuad 16-QAM simulation with a pair of 15Gbuad 16-QAM signals. After up-sampling to 4sps, the signal is pulse shaped by an RRC filter with a roll-off factor of 0.01. The two independent signals are up-converted to combine into a twin-SSB signal, and the guard bandwidth is set to 3GHz. The twin-SSB signal spectrum diagram is shown in Fig.1(b). The standard single-mode fiber (SSMF) link has dispersion of a 17ps/nm/km and the length of 80km. The white Gaussian noise loading module adjusts the OSNR of the received 16-QAM signal. A dispersive element introducing 1000ps/nm CD is applied for phase retrieval.

A. MCCA-PR convergence performance

Firstly, we analyze iteration speed and algorithm convergence of CCA-PR and MCCA-PR. As shown in Fig. 2(a), with the OSNR of 25dB, the CCA-PR scheme needs 20 iterations to converge, and the MCCA-PR scheme only requires 10 iterations. With CSPR of -1dB, the difference in the convergence speed of the two schemes is more prominent. It is worth noting that the MCCA-PR scheme has a less absolute phase error, which will effectively improve the correctness of the reconstructed signal. In subsequent simulations, the number of iterations for the MCCA-PR is fixed at 10, and the CCA-PR is set at 20. Fig.2(b) depicts the simulated BER versus CSPR under different OSNRs.

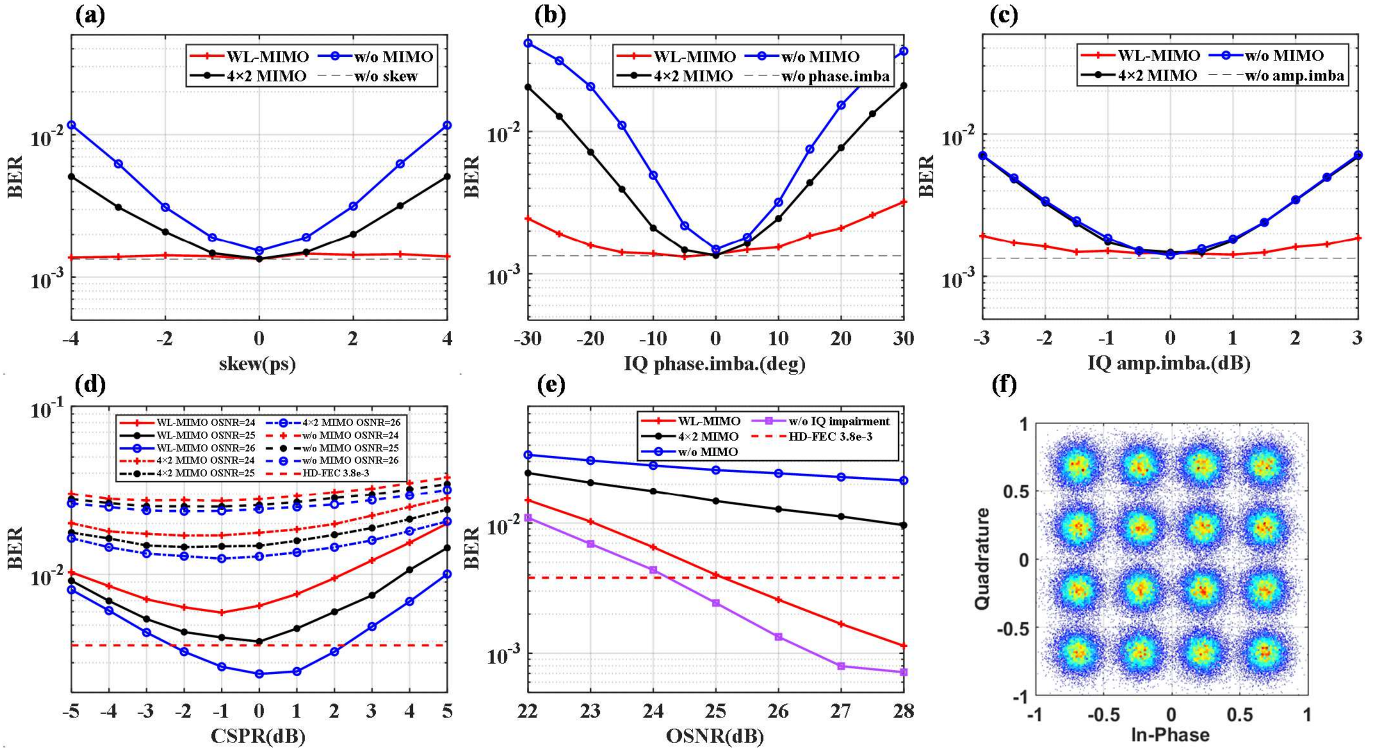

Fig.3 (a) BERs versus skew. (b) BERs versus IQ phase imbalance. (c) BERs versus IQ amplitude imbalance. (d) BER versus CSPR under different OSNRs. (e) BER versus OSNR under 0dB CSPR. (f) Constellation diagram, BER=2.2e-3.

With increasing OSNR, the optimal CSPR is 1dB for CCA-PR. The optimal CSPR of MCCA-PR increases with the increase of OSNR, between -1dB and 0dB Fig.2(c) depicts the simulated BER versus OSNR under different CSPRs. The results show that MCCA-PR only needs 10 iterations to achieve the same performance that CCA-PR achieve after 20 iterations, and MCCA-PR achieves around 1dB improvement of the OSNR penalty compared with CCA-PR under -1dB CSPR with the BER below 7% hard-decision forward error correction (HD-FEC) limit.

B. *WL-MIMO compensates for IQ impairments*

We demonstrate the impact of the three IQ impairments on system performance through simulations. Fig. 3(a) shows the results with IQ skew only, and the measured BER degrades with the increasing IQ skew. Although the BER is improved with the help of a 4×2 MIMO equalizer, it indicates that it cannot compensate IQ skew completely. In contrast, WL-MIMO is capable of compensating for IQ skew, even when the IQ skew is significant. The impact of the IQ phase imbalance and amplitude imbalance is considered, as shown in Fig. 3(b) and Fig. 3(c). The WL-MIMO equalizer can significantly improve the BER performance in the presence of severe phase imbalance and amplitude imbalance. However, with 4×2 MIMO used, the improvement is limited. This can be attributed to that fact that 4×2 MIMO cannot compensate IQ impairments and aliasing effects simultaneously.

To explore the performance of WL-MIMO and 4×2 MIMO, we introduce three kinds of impairments in the simulation simultaneously, where the IQ skew is fixed at 2ps, and the phase imbalance is fixed at 20deg and amplitude imbalance is fixed at 2dB. Fig. 3(d) shows the BER versus CSPR at different OSNRs. The measured BER after 4×2 MIMO equalization still be beyond 7% HD-FEC limit of 3.8e-3 even with high OSNR of 26dB. The optimal CSPR under the WL-MIMO equalizer case is 0dB, and when OSNR is 25dB, BER is lower than 7% HD-FEC. Fig. 3(e) shows BER versus OSNR under different equalization schemes. By comparison, we found that the 4×2 MIMO equalization scheme has poor compensation results, while WL-MIMO only requires less than 1dB OSNR penalty at 7% HD-FEC limit, compared with no transmitter IQ impairments case. Fig. 3(f) shows the constellation diagram after WL-MIMO equalization when OSNR=26dB and CSPR=0dB. The above results show that for the twin-SSB QAM signal with IQ impairments, the WL-MIMO scheme can compensate IQ impairments successfully and has superior performance than the 4×2 MIMO scheme.

IV. CONCLUSION

We propose a receiver DSP scheme combining fast field retrieval and transmitter IQ impairments compensation for direct detection of twin-SSB signal. Simulation results show that MCCA-PR based on the GS algorithm is superior to previous CCA-PR in terms of iteration speed and algorithm convergence by introducing amplitude error in the intensity constraint. As a result, the number of iterations is reduced to around 10. MCCA-PR has a 1dB OSNR sensitivity improvement at 7% HD-FEC, and the optimal carrier is reduced by 1-2dB compared with CCA-PR scheme. In the scenario of transmitter IQ impairments, up-conversion will cause interference between the two baseband signals for a twin-SSB signal, and a WL-MIMO is proposed to equalize the IQ impairments and the related interference . The WL-MIMO shows better tolerance to impairments compared with 4×2 MIMO regarding IQ skew, amplitude imbalance, and phase imbalance. In the case of 2ps IQ skew, 2dB amplitude imbalance, and 20deg phase imbalance, the WL-MIMO only requires less than 1dB OSNR penalty at 7% HD-FEC limit compared with no impairments case.

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