Transmitter Impairment Mitigation by 8×2 Widely Linear MIMO Equalizer with Improved Frequency Offset Tolerance

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Abstract: Transmitter impairment mitigation for 45GBaud DP-64QAM with 8×2 WL MIMO equalizer embedding CW-DA-WL phase estimator is demonstrated. Q penalty less than 0.5-dB with 8-ps IQ skew and 2.5-dB power imbalance are achieved with improved tolerance to frequency offset.

1. Introduction

To address the rapid growth in global traffic networks, there is a desire for higher symbol rates and higher-order modulation formats in fiber transmission systems [1]. However, as the symbol rate and modulation order increase, transceiver impairments, such as IQ imbalances, can significantly affect system performance. Typically, impairments in coherent receivers are assumed to be static and can be compensated through factory calibration [2]. However, the imperfections in the transmitter pose a greater challenge in the receiver's digital signal processing (DSP) scheme, as they are time-varying impairments combined with other channel impairments. To mitigate these impairments from the coherent transmitter side, a real-value multiple-input multiple-output (MIMO) equalizer followed by carrier phase recovery (CPR) has been proposed [3]. Furthermore, an 8×2 widely linear (WL) MIMO equalizer has been proposed to jointly calculate the MIMO coefficients and carrier phase obtained through a phase-locked loop (PLL) to further enhance performance [4]. However, these equalizers are only effective when the frequency offset is pre-compensated or pre-estimated. It is important to note that the PLL suffers from long delay and limited frequency offset estimation range, which can affect the accuracy of frequency offset estimation and subsequently affect system performance [5].

In this paper, we propose a method to improve the performance of 8×2 widely linear (WL) MIMO equalizer by embedding a complex-weighted, decision-aided, maximum-likelihood (CW-DA-ML) carrier phase and frequency offset estimator in the channel equalization process [6]. Different from the conventional methods, the embedded phase estimator can also track the residual frequency offset more than 15MHz after frequency offset pre-compensation. We also conduct an experimental demonstration with 45-GBaud dual polarization-64 quadrature amplitude modulation (DP-64QAM) formats after 80-km standard single mode fiber (SSMF) transmission. The experimental results show that our proposed method show better performance as well as the frequency offset tolerance than conventional 8×2 WL-MIMO equalizer in the mitigation of the coherent transmitter impairments.

2. 8×2 WL MIMO Equalizer with Carrier Phase Recovery

The proposed 8×2 WL MIMO equalizer with embedding CW-DA-ML phase estimator is shown in Fig. 1. The signals after initial frequency offset compensation are separated into X_I, X_Q, Y_I and Y_Q. The output samples z_X and z_Y of the 8×2 WL-MIMO equalizer are described as [4]:

$$z_i[k] = \sum_{j,m} g_{ij}[m] X_j[k-m] + \sum_{j,m} g_{ij*}[m] X_j^*[k-m] \tag{1}$$

where the filter tap coefficients g_{ij} and g_{ij*} are updated as [4]:

$$g_{ij}[m] \to g_{ij}[m] + 2\alpha l_i[k] X_j^*[k-m] \tag{2}$$

$$g_{ij*}[m] \to g_{ij*}[m] + 2\alpha l_i[k] X_j[k-m] \tag{3}$$

$$l_i[k] = d_i[k] - z_i[k] \tag{4}$$

where α is the step size, and l is the error between the true symbol d and the output sample z.

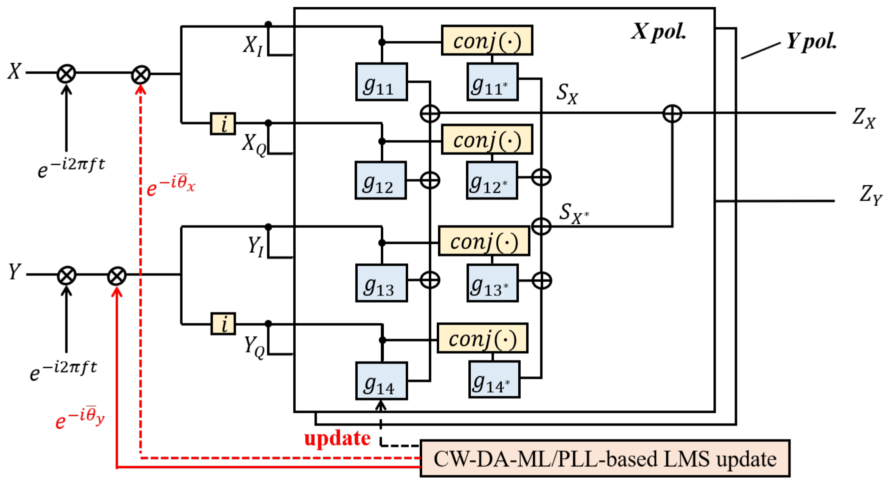

Fig. 1. Concept of the proposed 8×2 WL MIMO equalizer.

The key step of the proposed 8×2 WL MIMO equalizer is the embedding phase estimator after frequency offset compensation. Different from conventional phase estimator based on PLL, we propose to use CW-DA-ML phase estimator, where a complex reference phasor can be expressed as [6]:

$$V'(k+1) = C(k)\sum_{l=1}^{L} w_l(k)\, r(k-l+1)\, \hat{d}^*(k-l+1) \tag{5}$$

where L is the length of the estimator filter, $\hat{d}(k)$ is the decision of the kth symbol, $C^{-1}(k) = \sum_{l=1}^{L} \left|\hat{d}(k-l+1)\right|^2$ is a normalized factor, $r(k)$ is the received symbol after channel equalization and $w_l(k)$ is a complex weight. In theory, the complex weight $w_l(k)$ is designed to deal with the frequency offset. Under the least-mean-square-error criterion, the optimum $\hat{w}(k)$ is expressed as [6]:

$$\hat{w}(k) = \Phi^{-1}(k)\, s(k) \tag{6}$$

where $\Phi(k) = \sum_{l=1}^{k} C^2(l-1)\, y^*(l-1)\, y^T(l-1)$ is the L-by-L autocorrelation matrix, $y(k) = \left[r(k)\hat{d}^*(k)\cdots r(k-L+1)\hat{d}^*(k-L+1)\right]^T$ is a L-by-1 vector and $s(k) = \sum_{l=1}^{k} C(l-1)\, y^*(l-1)\, r(l)/\hat{d}(k)$ is a L-by-1 vector. It is noted that the matrix inversion $\Phi^{-1}(k)$ in Eq. (6) can be obtained recursively using the matrix inversion lemma without requirement of matrix inversion operation [6].

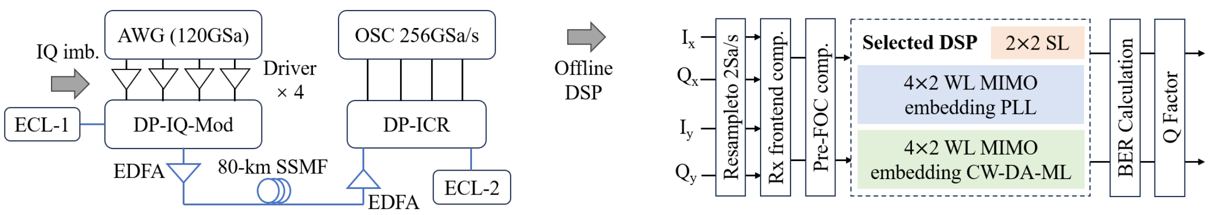

Fig. 2. Experimental setup of 45GBaud DP-64QAM transmission system and offline DSP.

3. Experimental Setup

The experimental setup is shown in Fig. 2(a). A 45 Gbaud 64-QAM signal waveform is generated offline, with roll-off factor of 0.01. The digital signal is then up-sampled and loaded to an arbitrary waveform generator (AWG, Keysight 8194A) operating at 120 GSa/s to achieve digital-to-analog conversion. The four analog signals are connected to a dual-polarization optical IQ modulator to achieve electrical-to-optical conversion via a tunable laser operating at ∼1550 nm. The amplified optical signal is then launched into the 80-km SSMF link. After fiber transmission, the optical signal is detected by a standard integrated coherent receiver (ICR). The electrical signal is t finally digitized by a 50 GHz digital storage oscilloscope (DSO, Keysight Infiniium UXR) operating at 256 GSa/s for further offline DSP. In the experimental demonstrations, the values of the IQ time skew and power imbalance at the x polarization are adjusted in the AWG. The values of the phase error are adjusted by tuning the bias voltage of the optical IQ modulator at the x polarization.

The offline DSP scheme is shown in Fig. 2 (b). The received signal is first resampled to 2Sa/sym. Then, a fixed receiver-side frontend compensation is applied. Next, the frame synchronization and pre-FOC is performed by correlation to the known overhead. Then three different MIMO equalizers are evaluated: (1) a 2×2 strictly linear (SL) MIMO equalizer, (2) a 8×2 WL MIMO equalizer with PLL phase estimator, (3) the proposed 8×2 WL MIMO equalizer with CW-DA-ML phase estimator. The tap length of the filter is set to 43 and the phase estimator length for CW-DA-ML is set to 9. The Q factor is computed based on the bit error rate.

4. Results and Discussion

The experimental results are shown in Fig. 3. The proposed 8×2 WL MIMO equalizer with CW-DA-ML phase estimator can provide an average 0.20 dB gain over conventional 8×2 WL MIMO equalizer with PLL phase estimator. The Q penalties are less than 0.5 dB up to a 2.5-dB gain imbalance, 0.3v voltage drift and 8 ps skew.

We then investigate the effect of the residual frequency offset on the system performance by changing the estimated frequency offset value. As shown in Fig. 4(a), the SNR penalty of CW-DA-ML phase estimator is less than 1dB when the residual frequency offset is less than 15MHz, showing much better tolerance than the PLL phase estimator. We also conduct a simulation to verify the phase tracking ability of the CW-DA-ML phase estimator. It can be seen in Fig. 4(b) that the CW-DA-ML phase estimator can track the fast phase variation due to the residual frequency offset. When the residual frequency offset is removed, the CW-DA-WL phase estimator can also successfully track the phase variation due to laser phase noise, as shown in Fig. 4(c).

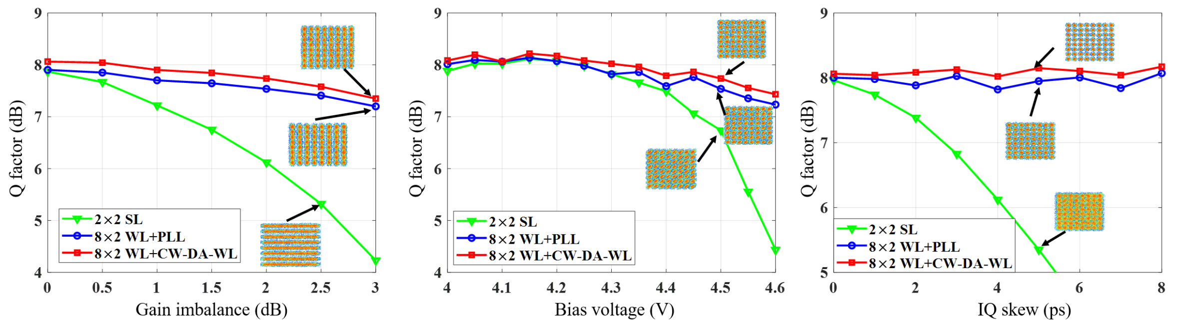

Fig. 3. Experimental results for 45-GBaud PM-64QAM transmission with transmitter impairments: (a) gain imbalance, (b) quadrature phase error by changing the bias, and (c) IQ skew.

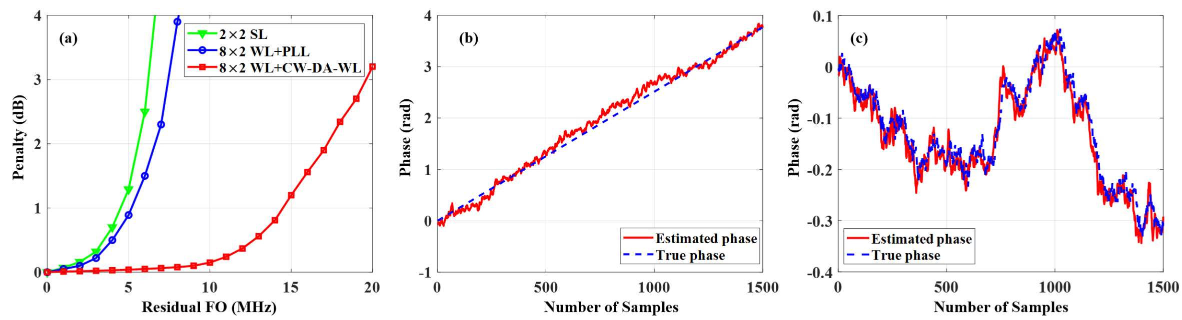

Fig. 4. (a) Experimental results of tolerance of residual frequency offset, (b) simulation results of the estimated phase with residual frequency offset, and (c) without residual frequency offset.

5. Conclusion

We propose to embed CW-DA-ML phase estimator in 8×2 WL MIMO equalizer for transmitter impairment mitigation with frequency offset tolerance up to 15 MHz. The experimental results show less than 0.5 dB Q-pearlites with 8 ps skew and 2.5 dB gain imbalance.

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