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Analysis and Compensation of Transmitter IQ Imbalance Based on MIMO Equalizer for Single-lane 800G DCI

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Abstract: We proposed a novel equalizer structure to compensate transmitter IQ imbalance for single-lane 800G coherent optical transmission system. The performances of equalizer are extensively validated using M-QAM modulation with single-wavelength 800Gbit/s net rate.
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1. Introduction

Coherent transmission has become the standard means of high data-rate transmission in metro and long-haul networks, and is evolving into the data center interconnect (DCI) space. However, due to the physical complexity of a typical coherent optical transmitter, the signal between the in-phase (I) and quadrature (Q) channels usually results in amplitude and phase imbalances, which is often referred to as transmitter IQ imbalance, and will exacerbate the system performance greatly if not compensated. Some works have been dedicated to the compensation of IQ imbalance by using digital signal processing (DSP). For quadrature phase-shift keying (QPSK) format, different methods have been employed such as the Gram-Schmidt orthogonalization procedure (GSOP) [1], the ellipse correction method (EC) [2], and IQ compensations based on the constant modulus algorithm (CMA) [3]. However, all of those methods are either draws considerably computational complexity or inapplicable for high-order modulation formats system. Recent works have investigated adaptive equalization architectures for IQ imbalance compensation. Various structures of complex-valued multiple-input-multiple-output (MIMO) adaptive equalizers are proposed for receiver imbalances. In [4] and [5], the equalizers of normal DSP procedure are replaced with their proposed structure, which performs IQ imbalance compensation and polarization de-multiplexing jointly. A blind adaptive source separation (BASS) structure was proposed in [6], which reduced computation complexity of the whole DSP procedure compared to equalization methods. This method shows better compatibility for high-order modulation formats, but are unable to compensate transmitter IQ imbalance. A post-DSP-based transmitter imbalance compensation filter is proposed [7], which shows that an equalizer after polarization de-multiplexing and carrier phase estimator can deal with transmitter IQ imbalance, but the performance will decrease for 800G systems.

In this work, we proposed a novel adaptive IQ imbalance compensation equalizer to compensate the transmitter IQ imbalance for 800Gbit/s coherent systems with polarization multiplexing (PM) for the first time. Simulation platform of three systems, PM-16QAM with 112GBaud, PM-32QAM with 96GBaud, PM-64QAM with 80GBaud are built to test and validate the performance of proposed equalizer.

2. Transmitter IQ imbalance model

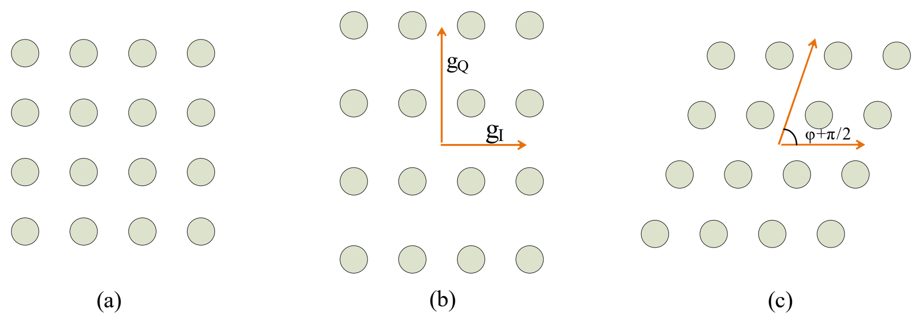

Fig.1. Imbalanced signal constellation of 16QAM. (a) Normal diagram; (b) With gain imbalance; (c) With phase imbalance.

The effect of transmitter IQ imbalance is modelled independently of the modulator type and can be seen as a linear combination of four input vectors, the I and Q port of x- and y- polarization, as shown in Fig. 1, respectively. A linear equalizer is thus capable to compensate IQ imbalance effectively.

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2. Simulation setup

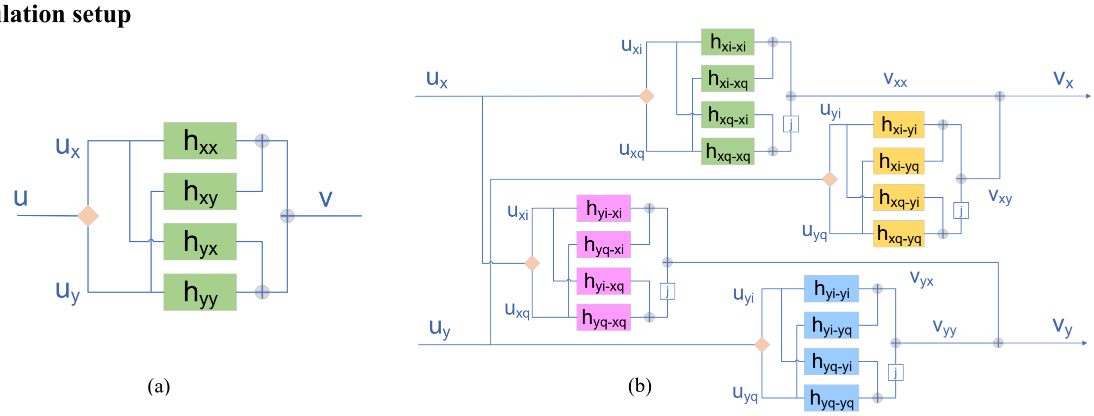


Fig.2. (a) Traditional 2×2 equalizer diagram; (b) Proposed equalizer diagram.

The proposed equalizer structure is shown in Fig. 2. We use u_{xi}, u_{xq}, u_{yi} and u_{yq} denoting the four vectors of received symbols, respectively. A normal 2×2 equalizer can only combine the x- and y- polarization and perform polarization de-multiplexing. However, the impact of IQ imbalance is a linear combination and rotation of those four vectors. Thus, we proposed a novel equalizer which deals with u_{xi}, u_{xq}, u_{yi} and u_{yq} separately. We employ sixteen real-valued filters to compensate IQ imbalance, and the tap coefficients are updated with DD-LMS algorithm.

To evaluate the performance of the proposed equalizer, we conduct simulations on 800Gbit/s scale in dual-polarization 16-, 32-, and 64-QAM coherent systems, and baud rates are 112G, 96G, 80G, respectively. At the Tx, pseudorandom binary sequences (PRBSs) with lengths of 2^{15}-1 bits are used for generating the signal along polarizations X and Y, respectively. Those sequences are then mapped into the M-QAM constellations. The QAM symbols are up-sampled to 2 samples per symbol and shaped by a root raised-cosine (RRC) filter with 202 taps. Their real and imaginary parts are applied to the I and Q inputs of the modulator, respectively, where the transmitter IQ imbalance is simulated. The signal is then impaired by phase noise of the transmitter laser and passes through a 20-km standard single-mode fiber (SSMF), whose transfer function consists of a loss of 0.2dB/km, a chromatic-dispersion (CD) value of 1700 ps/nm and PMD insertion, which includes a randomly generated polarization rotation, and the DGD is set to 1 ps. Additive white Gaussian noise (AWGN) from a preamplifier is then given to the signal. At the Rx, the local laser frequency is set to obtain a CFO of 0.1 GHz, and laser linewidth is the same as transmitter laser. The received signals are detected by a dual-polarization coherent receiver. To concentrate on the transmitter IQ imbalance, the Rx IQ imbalance coming from the imperfection of 90° optical hybrid units is not considered. The resolution of the ADCs is 8 bits and is assumed to be sufficiently high to neglect amplitude errors linked to quantization.

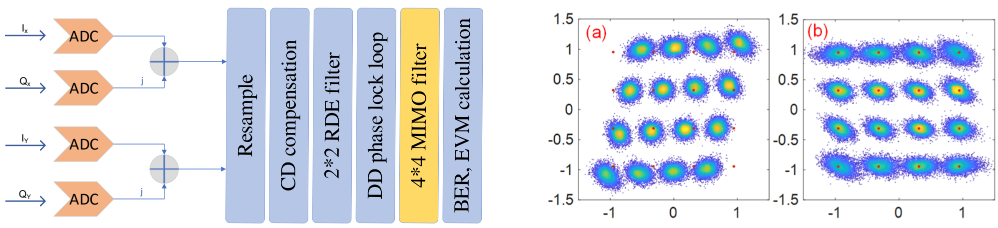


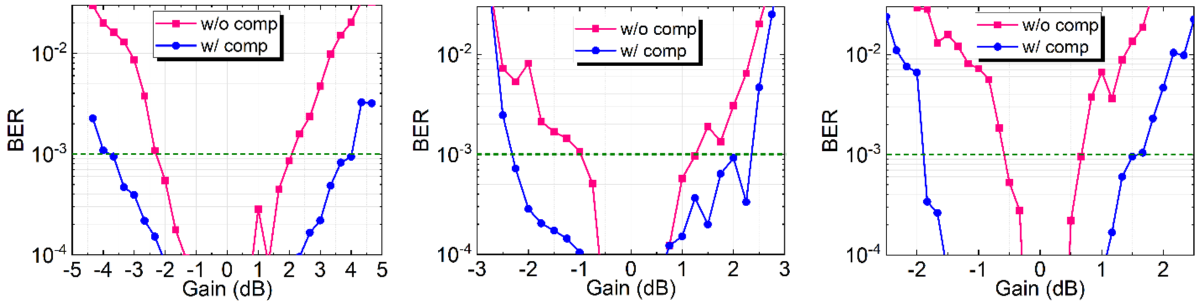
Fig. 3. Receiver DSP block. 16QAM constellations: (a) W/o IQ compensation, BER=8.43×10^{-2}; (b) W/ IQ compensation. BER=3.50×10^{-4}.

The offline DSP flow are shown in Fig. 3. In the offline DSP, output of 4 ADC channels is organized to 2 channel complex digital signal, where real part represents in-phase data and imaginary part represents quadrature data, respectively. Digitalized signals are then resampled with 2 samples per symbol, and a CD compensation module is applied. After that is a radius directed equalizer and a decision-directed phase lock loop (DD-PLL) for carrier frequency compensation and phase estimation. The proposed filter is located next, where 31 taps are used for each filter. The step-size parameter for the LMS algorithm is optimized for each system so that bit-error rate (BER) is minimized. The BER calculations are done twice before and after the compensation to evaluate the performance of each system. Results from X and Y polarization is calculated, and the final BER is an arithmetic mean of them.

3. Results and discussion

The BER performances of 800G systems versus transmitter gain and phase imbalance with PM-16QAM, PM-32QAM and PM-64QAM are shown in Fig. 4 and Fig. 5, respectively. The BER=1×10^{-3} is taken as a threshold. For PM-

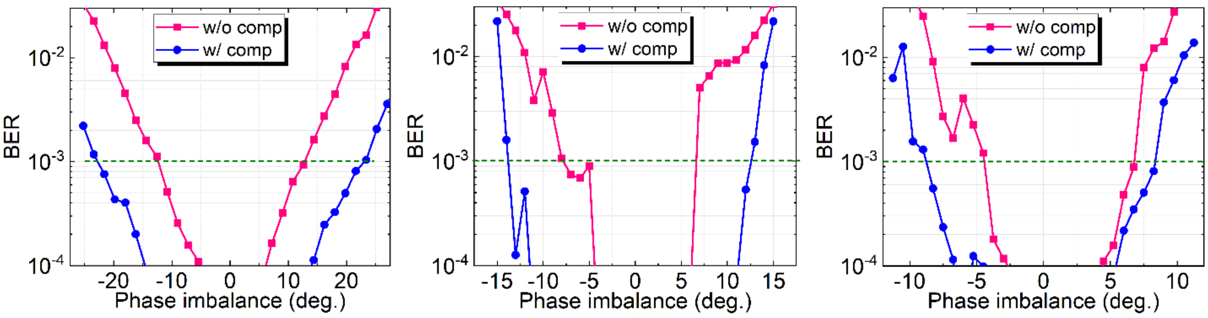
16QAM transmission, the gain imbalance tolerance increased from 2dB to 4dB after compensation, and the phase imbalance margin increased from 13 degrees to 24 degrees, as shown in Fig. 4(a) and Fig.5(a). For PM-32QAM, the gain imbalance tolerance and phase imbalance margin increased 1.3dB and 10 degrees, respectively. For PM-64QAM, the improvements of gain imbalance tolerance and phase imbalance margin are 1dB and 5 degrees, respectively. A 16QAM constellation diagram with gain imbalance equals to 3dB and phase imbalance equals to 20 degrees is shown in Fig. 3(a). It is obviously that such a diagram will result in poor transmission performance. Fig. 3(b) shows the IQ compensation 16QAM constellation with the proposed equalizer.



(a) (b) (c)

Fig. 4. BER performance for IQ gain imbalances w/o and w/ IQ compensation: (a) PM-16QAM; (b) PM-32QAM; (c) PM-64QAM.

For PM-16QAM, the proposed equalizer shows acceptable compensation ability even with severe imbalance such as 4 dB gain mismatch and 20° phase imbalance. However, for PM-32QAM and PM-64QAM systems, the compensation performance drops down much earlier. A possible cause for that is from the DD-LMS algorithm, as we used hard-decision to update the error function. In high-order modulation like 64QAM, denser constellation means wrong decision is likely to appear even with slight imbalance. A possible solution is to insert low-order modulation symbols like QPSK as pilot symbols to train the equalizer.



(a) (b) (c)

Fig. 5. BER performance for IQ phase imbalances w/o and w/ IQ compensation: (a) PM-16QAM; (b) PM-32QAM; (c) PM-64QAM.

4. Conclusions

We have proposed a novel 4×4 MIMO equalizer, which can compensate for IQ imbalances generated from improper bias and driving voltage from transmitter for high-speed 800G coherent systems. With intensive simulations, we have evaluated the impact of IQ imbalances on the performance of dual-polarization 16-, 32-, and 64-QAM systems and verified that the proposed scheme can effectively compensate IQ imbalances. Such a post-DSP equalizer is promising to be an effective solution for transmitter IQ imbalance for single-lane 800G DCI and higher-data-rate systems with high-order modulation formats.

5. References

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