



Modulation-format-transparent IQ imbalance estimation of dual-polarization optical transmitter based on maximum likelihood independent component analysis

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Abstract: We propose and experimentally demonstrate a modulation-format-transparent dual-polarization (DP) transmitter (Tx) in-phase/quadrature (IQ) imbalance estimation scheme based on maximum likelihood independent component analysis (ML-ICA). The proposed scheme can separate Tx IQ imbalance from polarization crosstalk and phase noise and achieve accurate IQ imbalance estimation without training data and the information of modulation format. Firstly, the complex-ML-ICA is used to implement format-transparent polarization de-multiplexing to remove polarization crosstalk; then the real-ML-ICA is employed to estimate inverse IQ mixing matrix and compensate Tx IQ imbalance/phase noise on each polarization channel. Inverse IQ mixing matrix contains the information of phase noise and Tx IQ imbalance; Finally, Tx IQ imbalance is derived from the inverse matrix by analytic method. The impact of Tx IQ imbalance on polarization demultiplexing and carrier phase recovery (CPE) is investigated by numerical simulation from three aspects of Jones space, Stokes space, and Kurtosis. The simulation results demonstrate the proposed scheme has strong robustness to phase noise, quantization noise, and amplified spontaneous emission (ASE) noise. The proposed ML-ICA algorithm is verified experimentally in polarization division multiplexing (PDM) quadrature phase-shift keying (QPSK)/8 quadrature amplitude modulation (QAM)/16QAM/64QAM systems. The experimental results show the scheme can accurately estimate Tx IQ imbalance within wide range in a format transparent manner.

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1. Introduction

In order to meet the growing demand on optical channel capacity, high order modulation format and polarization multiplexing technology have been widely used in coherent communication systems. IQ imbalance is a typical kind of hardware impairment in coherent optical Tx and receiver (Rx) [1]. Tx IQ imbalance is mainly introduced by amplitude mismatch in electrical amplifier or electro-optical response between I and Q channels and the phase deviation in the phase modulator [2,3]. Rx IQ imbalance is referred to the amplitude mismatch in the photodetectors (PD) or transimpedance amplifiers (TIA) and the phase deviation in the optical hybrid [4]. As an indispensable tool for system or module diagnosis, IQ imbalance monitoring technology has attracted increasing attentions recently. However, in PDM system with high order modulation format, IQ imbalance monitoring has difficulty in

separating IQ imbalance from polarization crosstalk and phase noise. Meanwhile, considering elastic optical network, modulation formats will be configured adaptively to improve transmission efficiency [5]. Therefore, in order to achieve the reliable performance monitoring and reconfigurable transceivers in intelligent optical network, it is critical to achieve IQ imbalance estimation for PDM transceiver in format-transparent manner.

Rx IQ imbalance estimation has been widely discussed previously, such as Gram-Schmidt orthogonalization procedure (GSOP) [6] or data statistical properties [7]. Regarding Tx IQ imbalance, polarization crosstalk, phase noise and IQ imbalance is coupled together. As a result, the polarization crosstalk and phase noise should be compensated firstly before the subsequent Tx IQ imbalance estimation. Unfortunately, the conventional schemes of polarization demultiplexing and phase recovery have degraded performance and even fail to work if severe Tx IQ imbalance is present.

For deal with the above difficulty, joint compensation algorithm is proposed as a possible solution. Joint polarization de-multiplexing and Tx IQ imbalance compensation schemes have been proposed, including constant modulus algorithm/radius directed equalization (BASS-CMA/RDE) [2] and complex conjugate CMA/RDE [4,8]. However, these schemes are modulation-format-dependent and have singularity problem, which is inherent in CMA/RDE. More importantly, the algorithms are designed for compensation purpose and is impossible to separate Tx IQ imbalance from polarization crosstalk. It is proposed that polarization crosstalk and phase noise can be compensated separately based on training or pilot data under Tx IQ estimation. Subsequently, the real-finite impulse response (FIR) based algorithm can be used to estimation Tx IQ imbalance [9,10]. However, the scheme is not proper for on-line system monitoring due to its training sequence manner. Furthermore, it is not applicable when large Tx IQ imbalance exists. This is due to the fact that polarization crosstalk and phase noise cannot be compensated under large Tx IQ estimation. Another problem is that it cannot deal with the case where the IQ phase imbalance exists. Recently, a DP- m -QAM transmitter optimization scheme based on machine learning algorithm is proposed and IQ imbalance be estimated in this scheme [11]. However, the scheme will fail to obtain actual IQ imbalance when amplitude and phase imbalance exist at the same time. In addition, the scheme requires an additional photodetector with increased cost. To the best of our knowledge, there is no available algorithm which is capable of all IQ imbalance estimation for DP-Tx in a modulation-format-transparent manner.

In our previous work, Rx and Tx IQ imbalances are separated and estimated in single polarization coherent optical communication system [12]. In this work a modulation-format-transparent DP-Tx IQ imbalance estimation scheme based on ML-ICA is proposed and experimentally demonstrated. In the scheme, a complex-ML-ICA is first used for polarization de-multiplexing. Then a real-ML-ICA is used on two respective polarization channels to estimate inverse IQ mixing matrix and compensate Tx IQ imbalance/phase noise. Finally, Tx IQ imbalance is estimated by analytical methods using inverse IQ mixing matrix. The proposed scheme is demonstrated experimentally with PDM-QPSK/8QAM/16QAM/64QAM Tx. The wide Tx IQ imbalance estimation range and excellent estimation accuracy are achieved successfully.

The rest of the paper is organized as follows: The impact of Tx IQ imbalance on the polarization demultiplexing and carrier phase estimation (CPE) is investigated by numerical simulation from three aspects of Jones space, Stokes space, and Kurtosis in section 2. The algorithm principle of ML-ICA is given in section 3. The proposed scheme is verified by experiment and simulation in section 4. Finally, the conclusion is presented in section 5.

2. The impact of Tx IQ imbalance

2.1 Tx module

A typical DP-Tx module is shown in Fig. 1, in which S_I and S_Q represent I and Q channels signals, respectively. g and θ represent Tx IQ amplitude and phase imbalance, respectively. The subscript “x/y” represents the X/Y polarization channel. On each polarization, the Tx IQ imbalance can be expressed as follows [13]:

$$\begin{bmatrix} \Re(E_{out}) \\ \Im(E_{out}) \end{bmatrix} \propto \mathbf{M} \begin{bmatrix} S_I \\ S_Q \end{bmatrix} = \begin{bmatrix} 1 & -g \sin(\theta) \\ 0 & g \cos(\theta) \end{bmatrix} \begin{bmatrix} S_I \\ S_Q \end{bmatrix} \quad (1)$$

where \mathbf{M} represents Tx IQ imbalance matrix.

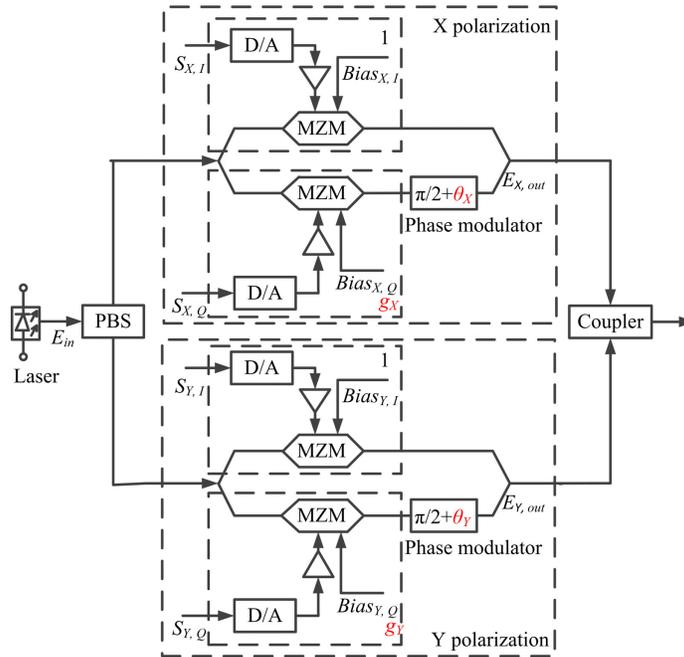


Fig. 1. The diagram of DP-Tx.

2.2 The impact of Tx IQ imbalance

The impact of Tx IQ imbalance is investigated by simulation in this section from three aspects of Jones vector, Stokes vector, and Kurtosis. QPSK signals are used as an example to reveal the impact of IQ imbalance more intuitively. Jones matrix \mathbf{J} (in Eq. (2)) is used on two polarization channels to model polarization crosstalk [14] and the phase difference matrix \mathbf{D} (Eq. (3)) is used on I and Q channels of each polarization to represent the phase difference between the Tx and Rx oscillator [15].

$$\mathbf{J} = \begin{bmatrix} \cos \kappa e^{j\xi} & -\sin \kappa e^{j\eta} \\ \sin \kappa e^{-j\eta} & \cos \kappa e^{-j\xi} \end{bmatrix} \quad (2)$$

$$\mathbf{D} = \begin{bmatrix} \cos \varphi & -\sin \varphi \\ \sin \varphi & \cos \varphi \end{bmatrix} \quad (3)$$

where ξ and η represent the phase angle related to polarization, κ and φ represent the polarization azimuth angle between fast axis and slow axis and phase difference between the Tx and Rx oscillator, respectively. ξ and η are set to 30 degrees and 50 degrees, respectively. $\kappa = 0$ and $\varphi = 0$ represent no polarization crosstalk and phase difference, respectively. Besides, the Jones vector $[E_x \ E_y]^T$ can be transformed into the Stokes vector $[S_0 \ S_1 \ S_2 \ S_3]^T$ by the following equation [16]:

$$\begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} E_x E_x^H + E_y E_y^H \\ E_x E_x^H - E_y E_y^H \\ E_x^H E_y + E_x E_y^H \\ -i E_x^H E_y + i E_x E_y^H \end{bmatrix} \quad (4)$$

Firstly, the IQ imbalance impact on constellation in Jones space is considered. In conventional polarization de-multiplexing and CPE algorithms, such as RDE and blind phase search (BPS) [17], the standard constellation is used as the reference to mitigate signal impairments. However, Tx IQ imbalance will distort the constellation of the received signals and the constellation distortion from square to parallelogram can be found in Fig. 2(b) and 2(c). In this situation, it is obvious that the original standard constellation cannot be employed as reference. Therefore, the conventional algorithms have degraded performance and even fail to work in presence of Tx IQ imbalance due to severe decision error. Therefore, these algorithms which use the standard signal as reference cannot deal with the estimation of DP-Tx IQ imbalance.

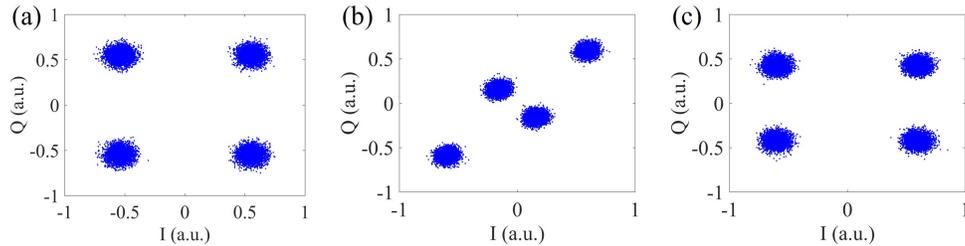


Fig. 2. Received QPSK signals in Jones space. QPSK Constellation (a) without IQ imbalance; (b) QPSK Constellation with 30-degree IQ phase imbalance; (c) QPSK Constellation with 3 dB IQ phase imbalance.

Next, the impact of Tx IQ imbalance on the signal distribution in Stokes space is discussed. Stokes space analysis has been used for polarization de-multiplexing with modulation-format-transparency. In Stokes space, the normal vector of least square fitting plane is parallel to S_1 -axis without polarization crosstalk and IQ imbalance, as shown Fig. 3(a). Therefore, by rotating received signals to make the normal vector of least square fitting plane parallel to S_1 -axis, polarization de-multiplexing is implemented. However, IQ phase imbalance will disarrange the distribution of signal constellation. With a large phase imbalance, the normal vector may be vertical to S_1 -axis, as shown in Fig. 3(b) and 3(c). As a result, based on the least square fitting method, the Stokes space analysis based polarization de-multiplexing algorithm fails to work. Therefore, Stokes space analysis scheme is not applicable in presence of phase imbalance. Meanwhile, it can be seen that IQ amplitude imbalance only causes the constellation points to slide along the least square fitting plane and does not change the direction of the normal vector, as shown in Fig. 3(d) and 3(e). This indicates that IQ amplitude imbalance has negligible impact on Stokes space analysis based polarization demultiplexing.

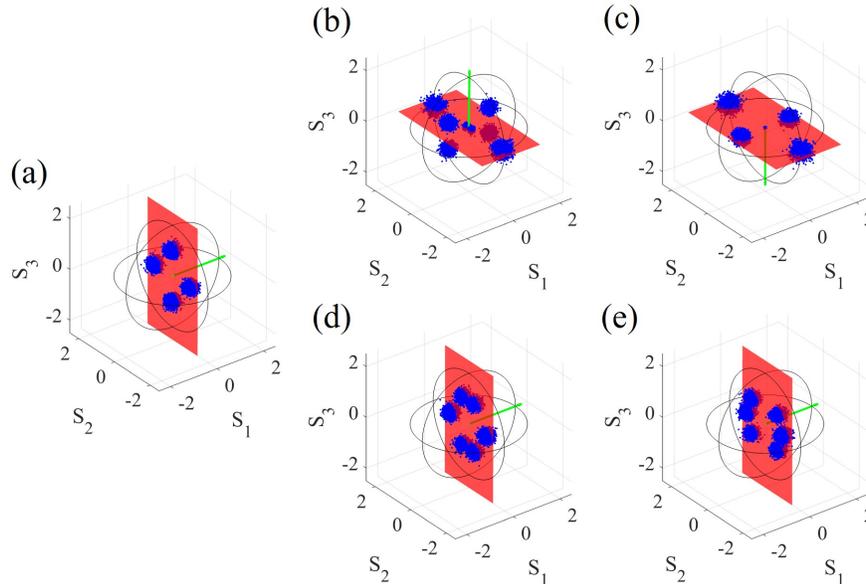


Fig. 3. Received QPSK signals in Stokes space. QPSK constellation (a) without IQ imbalance; (b) with 30-degree IQ phase imbalance; (c) with 45-degree IQ phase imbalance; (d) with 3 dB IQ amplitude imbalance; (e) with 6 dB IQ amplitude imbalance. Blue dot is constellation point; red plane is the least square plane; green line is the normal vector of the least squares plane.

Finally, the feasibility of ICA based polarization demultiplexing, IQ imbalance compensation and phase recovery are investigated by analyzing Kurtosis under different polarization crosstalk and phase difference. In the simulation, 28 Gbaud QPSK signals are used and OSNR is set to 14 dB, which corresponds to the theoretical BER of 10^{-3} . Kurtosis is a common measure of non-Gaussian and the basic principle of ICA is to separate independent components by finding the maximum nongaussianity. The bigger the absolute Kurtosis is, the stronger the nongaussianity is. It is mean that independent components have been separated when Kurtosis is up to maximum [18]. Figure 4 show that the kurtosis always reaches the maximum when polarization azimuth is 0 under different IQ imbalances. It is mean that if ICA converges successfully polarization demultiplexing can be achieved even large IQ imbalance exists. Similarly, Fig. 5 shows that the maximum kurtosis always appears when both IQ imbalance and phase difference are 0. Thus, ICA can be used to implement joint IQ imbalance compensation and carrier phase recovery in theory.

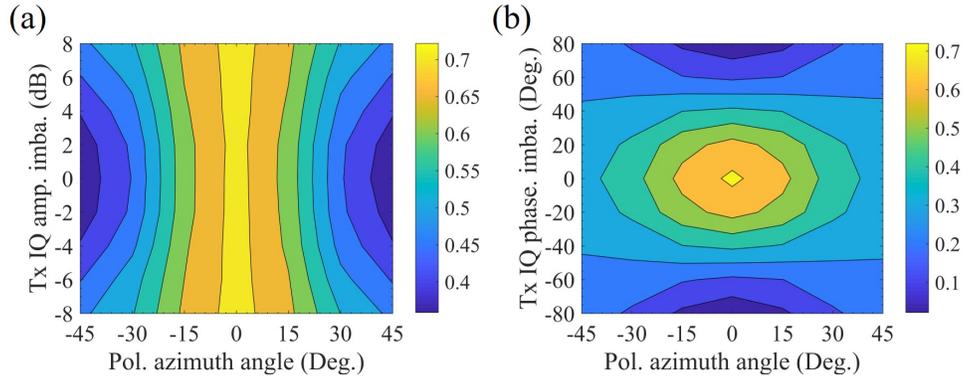


Fig. 4. Kurtosis of received signal (a) under polarization crosstalk and IQ amplitude imbalance (b) under polarization crosstalk and IQ phase imbalance.

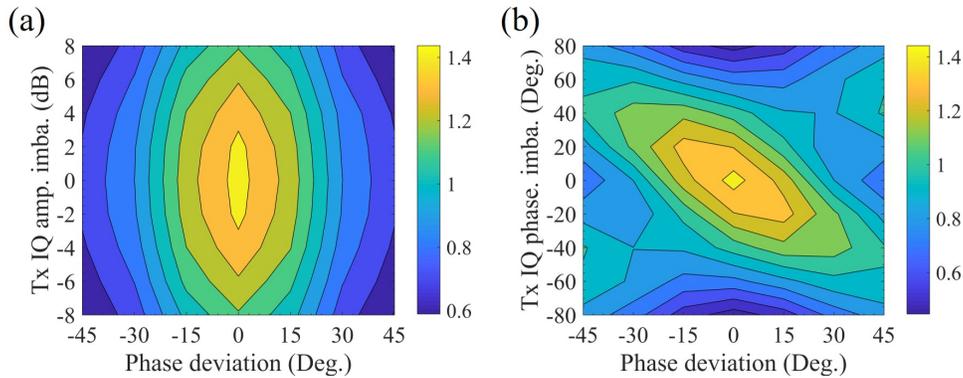


Fig. 5. Kurtosis of received signals (a) under phase difference and IQ amplitude imbalance (b) under phase difference and IQ phase imbalance.

3. Algorithm principle

3.1 ML-ICA algorithm

ICA algorithm is a kind of statistical analysis technique, which can reveal the characteristics of original signal and channel by using the received signal only and is suitable for deal with blind source separation (BSS) problem. In theory, polarization de-multiplexing, IQ imbalance compensation, and phase noise compensation is regarded as the BSS problem [19] and can be implemented based on ICA algorithm. In previous publications, ICA algorithm is considered to be inherently independent of modulation format and immune to singularity [20,21]. In addition, the discussion in the previous section has proved that ICA algorithm is also immune to IQ imbalance for polarization de-multiplexing or CPE. Therefore, ICA is promising for implementing modulation-format-transparent DP-Tx IQ imbalance estimation.

The ML-ICA algorithm is a typical ICA algorithm, which employs ML estimation to maximize the mutual information between the input and output signals of ML-ICA. When the mutual information reaches the maximum, the statistical independence of output signals has the highest level. ML-ICA can be generally implemented by the natural gradient equations with the following equations [22]:

$$\mathbf{Z}_{out,k} = \mathbf{W}_k \mathbf{Z}_{in,k} \quad (5)$$

$$\mathbf{W}_{k+1} = \mathbf{W}_k + \mu (\mathbf{I} + \varphi(\mathbf{Z}_{out,k}) \mathbf{Z}_{out,k}^H) \mathbf{W}_k \quad (6)$$

$$\varphi(\mathbf{Z}_{out,k}) = \partial \ln p(\mathbf{Z}_{out,k}) / \partial \mathbf{Z}_{out,k} = \mathbf{p}'(\mathbf{Z}_{out,k}) / p(\mathbf{Z}_{out,k}) \quad (7)$$

where k , \mathbf{Z}_{in} , \mathbf{Z}_{out} , \mathbf{W} , μ , $\varphi(\cdot)$, and $p(\cdot)$ represent the time index, input signal, output signal, inverse mixture matrix, step size, score function, and probability density function, respectively. “ $(\cdot)^H$ ” and “ $(\cdot)'$ ” represent the conjugate transposition and derivation, respectively. The usual probability density functions are as follows:

$$\ln p^+(\mathbf{Z}_{out,k}) = \alpha_1 - 2 \ln(\cosh(\mathbf{Z}_{out,k})) \quad (8)$$

$$\ln p^-(\mathbf{Z}_{out,k}) = \alpha_2 - (\mathbf{Z}_{out,k}^2 / 2 - \ln(\cosh(\mathbf{Z}_{out,k}))) \quad (9)$$

where α_1 and α_2 represent fixed constant. In this paper, $p^+(\cdot)$ and $p^-(\cdot)$ are used as probability density function in polarization de-multiplexing and Tx IQ imbalance/phase noise compensation, respectively.

3.2 ML-ICA based DP-Tx IQ imbalance estimation

As shown in Fig. 6, IQ imbalance estimation of DP-Tx based on ML-ICA is consisted of polarization de-multiplexing, Tx IQ imbalance/phase noise compensation, and Tx IQ imbalance estimation. k is omitted in the following discussion for brevity.

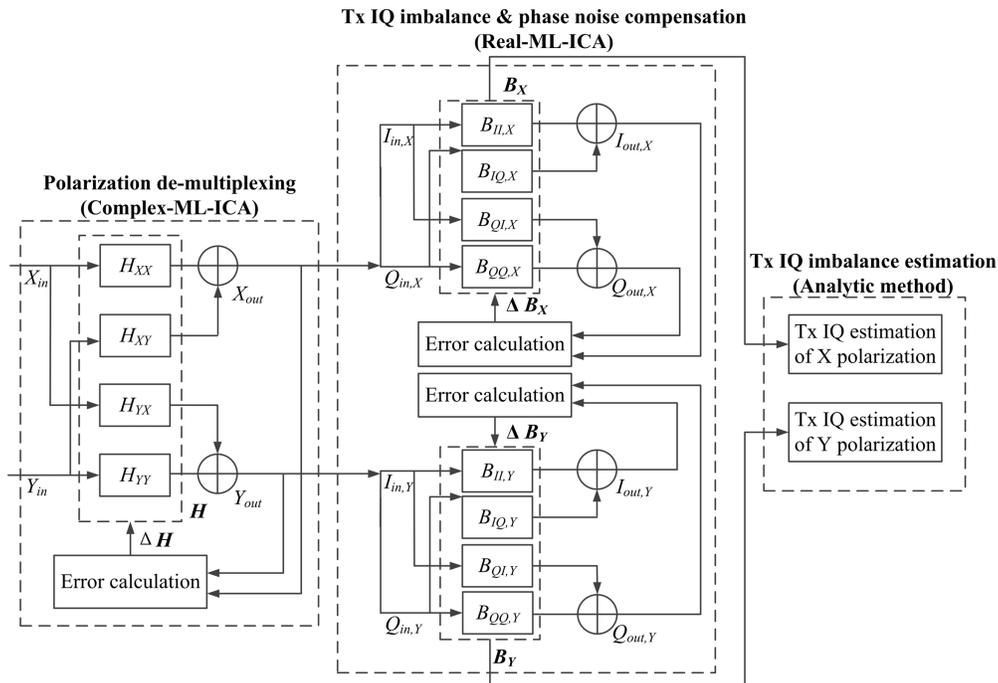


Fig. 6. The diagram of ML-ICA based DP-Tx IQ imbalance estimation algorithm.

3.2.1 Complex-ML-ICA based polarization de-multiplexing

For polarization de-multiplexing, complex-ML-ICA is employed to estimate inverse Jones matrix \mathbf{H} by substituting the below parameters into Eqs. (5)-(8) [16].

$$\mathbf{Z}_{in} = \begin{bmatrix} X_{in} \\ Y_{in} \end{bmatrix}, \mathbf{Z}_{out} = \begin{bmatrix} X_{out} \\ Y_{out} \end{bmatrix}, \mathbf{W} = \mathbf{H} = \begin{bmatrix} H_{XX} & H_{YX} \\ H_{XY} & H_{YY} \end{bmatrix} \quad (10)$$

where X and Y represent the signals of two polarizations. Polarization crosstalk is processed separately in this stage. It is noteworthy that complex-ICA can exploit both magnitude and phase information and has strong robustness to noise [23]. Compared with other ICA algorithms which only consider magnitude information, complex-ICA can tolerate more IQ imbalance. However, the frequency offset is detrimental to the convergence of complex-ICA and should be compensated in advance.

3.2.2 Real-ML-ICA based Tx IQ imbalance and phase noise compensation

For IQ imbalance/phase noise compensation, the following expressions are substituted into Eqs. (5)-(7) and (9) to estimate inverse IQ mixing matrix \mathbf{B} .

$$\mathbf{Z}_{in} = \begin{bmatrix} I_{in,X/Y} \\ Q_{in,X/Y} \end{bmatrix}, \mathbf{Z}_{out} = \begin{bmatrix} I_{out,X/Y} \\ Q_{out,X/Y} \end{bmatrix}, \mathbf{W} = \mathbf{B}_{X/Y} = \begin{bmatrix} B_{II,X/Y} & B_{IQ,X/Y} \\ B_{QI,X/Y} & B_{QQ,X/Y} \end{bmatrix} \quad (11)$$

where I and Q represent the I and Q components of signals. Obviously, Tx IQ imbalance and phase noise information are coupled in \mathbf{B} . Tx IQ imbalance will be extract from \mathbf{B} in the next section.

3.2.3 Analytic method based Tx IQ estimation

If ignoring quantization noise and ASE noise, the signal evolution process can be shown as Fig. 7. In Fig. 7, \mathbf{P}_N , \mathbf{P}_1 , ω and α represent the phase noise matrix related to laser linewidth, phase rotation along fiber channel, frequency offset, and scale factor caused by normalization, respectively.

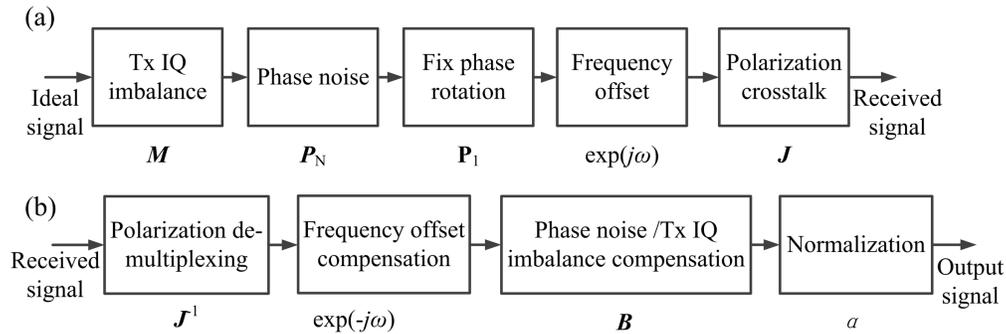


Fig. 7. Signal evolution process. (a) The introduction of signal impairment; (b) The compensation of signal impairment.

Assuming ideal polarization de-multiplexing and frequency offset compensation are achieved, the output signals of IQ imbalance/phase noise compensation based on real-ML-ICA can be expressed:

$$\begin{bmatrix} I_{out} \\ Q_{out} \end{bmatrix} \approx \alpha \mathbf{B} \mathbf{P}_1 \mathbf{P}_N \mathbf{M} \begin{bmatrix} I_{ideal} \\ Q_{ideal} \end{bmatrix} \quad (12)$$

where I_{ideal} and Q_{ideal} represent the ideal I and Q components of signals, respectively. It is noteworthy that \mathbf{P}_1 and \mathbf{P}_N can be considered together and have the expression of $[\cos(\psi) \ -\sin(\psi); \sin(\psi) \ \cos(\psi)]$. If ML-ICA is implemented perfectly, $[I_{out} \ Q_{out}]^T = [I_{ideal} \ Q_{ideal}]^T$. Therefore, from Eq. (12) the following equation is derived:

$$\alpha \mathbf{B} \mathbf{P}_1 \mathbf{P}_N \mathbf{M} = \alpha \begin{bmatrix} B_{II} & B_{IQ} \\ B_{QI} & B_{QQ} \end{bmatrix} \begin{bmatrix} \cos(\psi) & -\sin(\psi) \\ \sin(\psi) & \cos(\psi) \end{bmatrix} \begin{bmatrix} 1 & -g \sin(\theta) \\ 0 & g \cos(\theta) \end{bmatrix} = \mathbf{I} \quad (13)$$

Considering \mathbf{B} has been estimated, g and θ can be calculated from Eq. (13) according to the element equivalence of corresponding position on both sides of matrix equation. The analytic equations of Tx IQ imbalance can be derived as follows:

$$\psi = -\arctan(B_{OI} / B_{OO}) \quad (14)$$

$$\alpha = 1 / (B_{II} \cos(\psi) + B_{IO} \sin(\psi)) \quad (15)$$

$$\theta = \arctan((-B_{II} \sin(\psi) + B_{IO} \cos(\psi)) / (B_{II} \cos(\psi) + B_{IO} \sin(\psi))) \quad (16)$$

$$g = 1 / (-\alpha \sin(\theta)(B_{OI} \cos(\psi) + B_{OO} \sin(\psi)) + \alpha \cos(\theta)(-B_{OI} \sin(\psi) + B_{OO} \cos(\psi))) \quad (17)$$

Finally, the influence of noise is mitigated by averaging the estimated parameters. Then Tx IQ imbalance is separated from polarization crosstalk and phase noise and estimated successfully.

4. Results and analysis

4.1 Simulation analysis

The simulation system is built to analyze the robustness of the proposed scheme, as shown in Fig. 8. In Tx DSP module, 2^{16} 4-level random signals are used to generate optical PDM-16QAM signal. These signals are resampled at 3 samples per symbol and then filtered by a raise cosine filter with roll-off 1. Subsequently, digital-to-analog conversion (DAC) is simulated by quantization and Tx IQ imbalance is introduced by Tx IQ imbalance matrix \mathbf{M} . The polarization amplitude and phase imbalances on X and Y polarization are set to 3 dB and 20 degrees, respectively. In optical link, ASE noise is added to set OSNR and then polarization crosstalk is achieved with Jones matrix \mathbf{J} with 30-degree κ , 30-degree ξ , and 50-degree of η . Phase noise is simulated in Tx and local oscillation (LO) lasers module with a Wiener process [24]. Ideal coherent receiver is used and then the received signals is quantized to simulate analog-to-digital conversion (ADC). In Rx DSP module, square filtering [18] are used to implement time recovery. The complex-ML-ICA is used to implement polarization de-multiplexing. Then, the real-ML-ICA is used on each polarization to implement Tx IQ imbalance/phase noise compensation and estimate inverse IQ mixing matrix. Finally, the analytic method is used to estimate Tx IQ imbalance based on the estimated mixing matrix. The tolerance of the proposed scheme on phase noise, quantization noise, and ASE noise are investigated in this section. 28 Gbaud PDM-16QAM signals are used and 20 data sets are collected in each simulation.

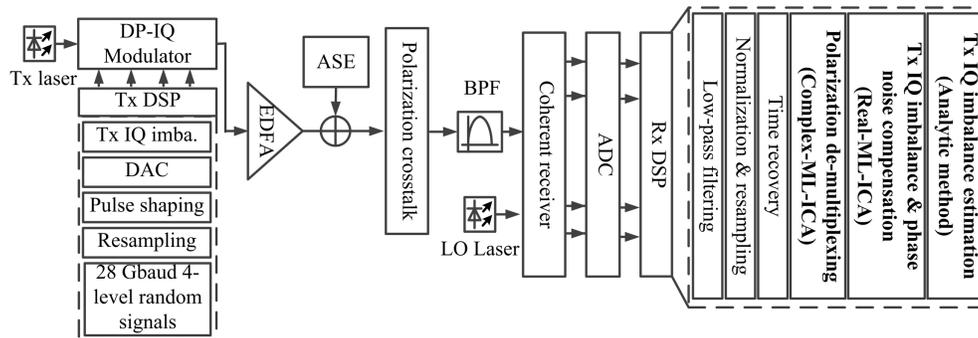


Fig. 8. The diagram of simulation system of 28 Gbaud PDM-16QAM coherent optical communication system.

Firstly, the proposed scheme is tested under different laser linewidth. The OSNR is set to 21 dB and the resolution of DAC/ADC is set to 5.5 bits. The simulation results are shown in

Fig. 9(a) and 9(d). With the linewidth is increased from 100 kHz to 500 kHz, the amplitude imbalance error is increased from 0.13 dB to 0.3 dB and the related error variance is increased from 5.3×10^{-3} to 4.4×10^{-2} ; the phase imbalance error is increased from 0.55 degree to 1.14 degrees and the related error variance remains near 0.08. Considering the linewidth of commercial laser is around 100 kHz, the phase noise has acceptable influence on the proposed scheme in practical application.

Next, the proposed scheme is tested under different resolution of DAC/ADC, as shown in Fig. 9(b) and 9(e). The OSNR is also set to 21 dB and the linewidth is set 100 kHz. With the resolution of DAC/ADC from 3 bits to 7 bits, the amplitude imbalance error and the related error variance remain near 0.077 and 3.4×10^{-5} , respectively; the phase imbalance error the related error variance remains near 0.46 and 0.05, respectively. The simulation results shown that the proposed algorithm has strong robustness on quantization noise.

Finally, the proposed scheme is tested under different OSNR, as shown in Fig. 9(c) and 9(f). The linewidth is set to 100 kHz and the resolution of DAC/ADC is set to 5.5 bits. With the OSNR is decreased from 27 dB to 13 dB, the amplitude imbalance error and the related error variance are increased from 0.022 to 0.36 and 4×10^{-6} to 6×10^{-4} , respectively; the phase imbalance error is increased from 0.15 to 2.4 the related error variance remains near 0.05. The simulation results demonstrate that the proposed maintain excellent accuracy in a wide range of OSNR. Considering the theory BER is around 10^{-3} when OSNR is set as 21 dB, the proposed has enough robustness on ASE noise.

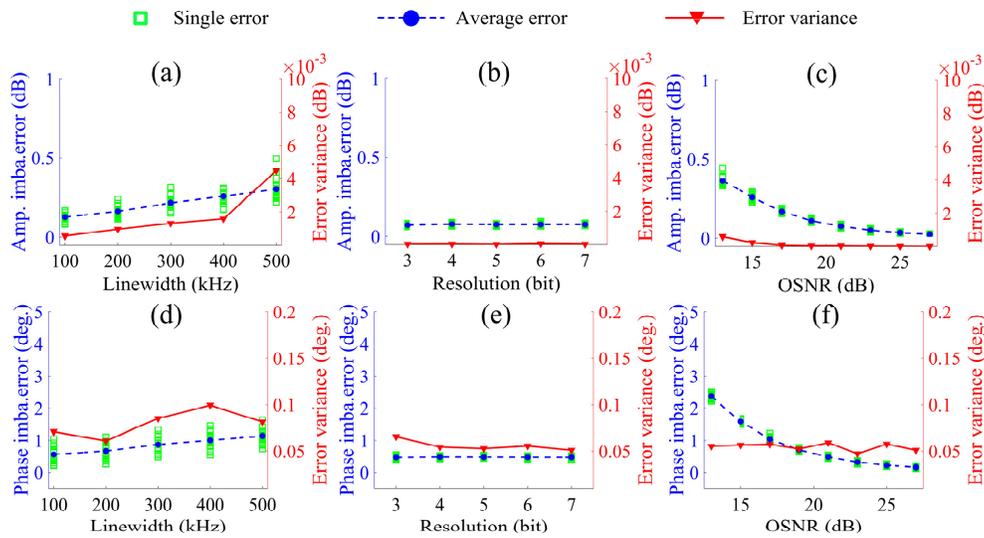


Fig. 9. The tolerance of the proposed scheme on phase noise, quantization noise, and ASE noise.

4.2 Experimental validation

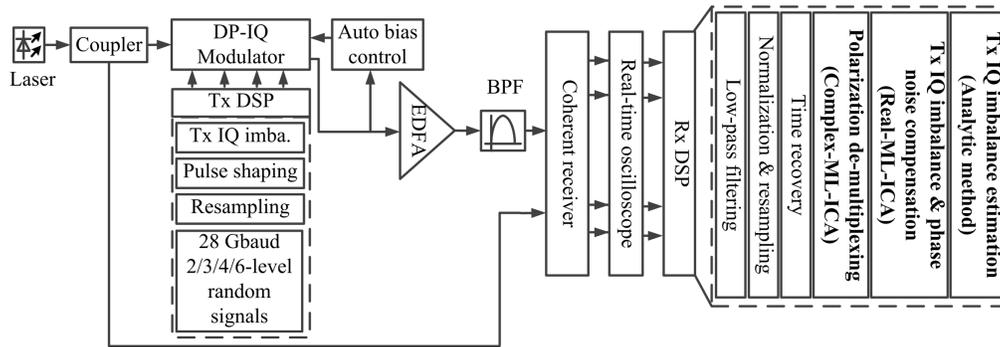


Fig. 10. The diagram of experimental system of 28 Gbaud PDM-QPSK/8QAM/16QAM/64QAM coherent optical communication system.

For focusing on DP-Tx IQ imbalance estimation and estimation range evaluation, the homodyne detection is employed in this paper, as shown in Fig. 10. In each polarization, 2^{16} 2/3/4/6-level random signals are used for optical PDM-QPSK/8QAM/16QAM/64QAM signal generation. Tx IQ imbalances, including amplitude and phase imbalances, are digitally introduced by Tx IQ imbalance matrix \mathbf{M} . A continuous wave laser with 100 kHz linewidth is used as optical carrier. The processed signals are generated by arbitrary waveform generator (AWG, Keysight M8196A) to drive optical DP-IQ modulator (Fujitsu FTM7992HM). An integrated coherent receiver (Fujitsu FIM24706EB) is used to detect optical signals. The detected signals are sampled by a real-time oscilloscope at 80GSample/s. The sampled data was processed offline in Rx DSP module, as shown in Fig. 10. The Rx DSP module is the same as that of the previous subsection, as shown in Fig. 9 and Fig. 10.

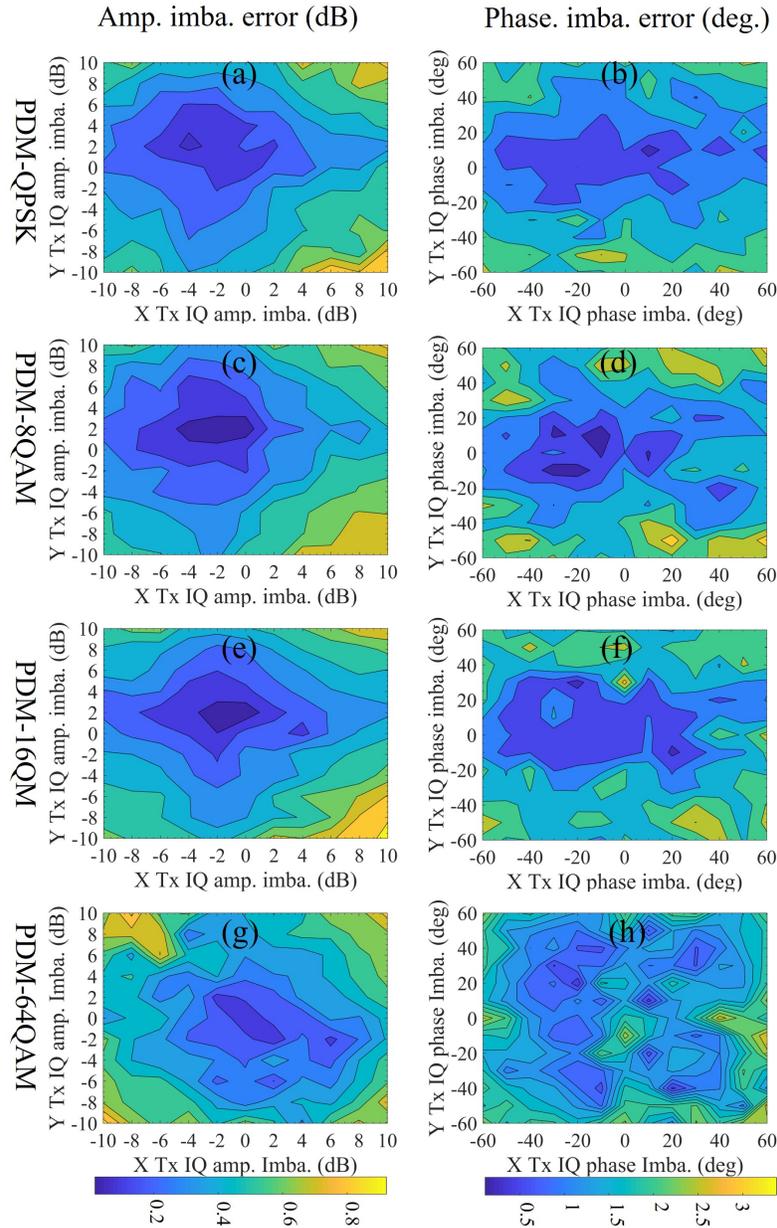


Fig. 11. Tx IQ imbalance estimation error of ML-ICA in PDM-QPSK/8QAM/16QAM/64QAM system.

The proposed algorithm is experimentally investigated in PDM-QPSK/8QAM/16QAM/64QAM systems with different Tx IQ amplitude and phase imbalances imposed on two polarizations. The results show the scheme has excellent estimation range and good estimation accuracy for three modulation formats. Regarding Tx IQ amplitude imbalance, the scheme has the estimation range of $[-10\ 10]$ dB within the 1 dB error. Regarding Tx IQ phase imbalance, the estimation range can be as large as $[-60\ 60]$ degrees within the 4-degree error (Fig. 11).

Finally, a general case that all kind of IQ imbalances on each polarization are different is considered in order to prove the stability of ML-ICA. In X polarization, IQ amplitude/phase imbalance is set to 4 dB/30 degrees. In Y polarization, IQ amplitude/phase imbalance is set to -2 dB/-10 degrees. Experimental results demonstrate that the scheme has accurate IQ imbalance estimation performance under different modulation formats even when different IQ imbalances exist in two polarizations, as shown in Table 1. Therefore, the proposed algorithm can accurately estimate IQ imbalance of DP-Tx within a wide range in a blind manner for different modulation format.

Table 1. ML-ICA under different IQ imbalances on each polarization.

	X IQ amp. imba. (dB)	Y IQ amp. imba. (dB)	X IQ phase imba. (deg.)	Y IQ phase imba. (deg.)
Actual value	4	-2	30	-10
QPSK est. value	4.1819	2.0976	29.0125	9.1888
8QAM est. value	4.1916	2.0417	29.7770	9.3843
16QAM est. value	3.8415	1.9485	29.2253	11.3190
64QAM est. value	3.6222	1.8225	32.2417	9.9324

5. Conclusions

We proposed and experimentally demonstrated a modulation-format-transparent DP-Tx IQ imbalance estimation scheme based on ML-ICA. In first step, the complex-ML-ICA is used to implement polarization de-multiplexing in presence of Tx IQ imbalance; then the real-ML-ICA is employed to implement inverse IQ mixing matrix estimation and Tx IQ imbalance/phase noise compensation on each polarization channel; Finally, an analytic method is employed for deriving Tx IQ imbalance based on the estimated inverse IQ mixing matrix. The proposed scheme has been verified to have strong robustness to phase noise, quantization noise, and ASE noise in simulation. Subsequently, the experimental results shown that the proposed scheme can estimate [-10 10] dB Tx IQ amplitude imbalance within 1 dB error and [-60 60] degrees Tx IQ phase imbalance within 4-degree error in the PDM-QPSK/8QAM/16QAM/64QAM system. Therefore, it has application potential to diagnose DP-Tx modules employed in the future elastic optical network.

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