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A novel transmitter IQ imbalance and phase noise suppression method utilizing pilots in PDM CO-OFDM system

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ABSTRACT

In this paper, we develop a novel pilot structure to suppress transmitter in-phase and quadrature (Tx IQ) imbalance, phase noise and channel distortion for polarization division multiplexed (PDM) coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems. Compared with the conventional approach, our method not only significantly improves the system tolerance of IQ imbalance as well as phase noise, but also provides higher transmission speed. Numerical simulations of PDM CO-OFDM system is used to validate the theoretical analysis under the simulation conditions: the amplitude mismatch 3 dB, the phase mismatch 15°, the transmission bit rate 100 Gb/s and 560 km standard signal-mode fiber transmission. Moreover, the proposed method is 63% less complex than the compared method.

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1. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) has obvious advantages against chromatic dispersion (CD) and polarization mode dispersion (PMD) and can provide high speed transmission with Polarization division multiplexed (PDM) technique joint in the system [1,2]. However, the transmitter in-phase and quadrature (Tx) IQ imbalance which includes the imperfect amplitude and phase mismatch during the signal IQ modulation and the phase noise which includes common phase error (CPE) and inter-carrier-interference (ICI) would seriously decrease the reliability of PDM CO-OFDM system [3,4].

Previously, some compensation methods for Tx IQ imbalance have been proposed [5,6]. A novel training symbol structure is designed to estimate the Tx IQ imbalance factor and channel distortion independently in CO-OFDM system in [5]. In [6], in order to compensate the Tx IQ imbalance and channel distortion for PDM CO-OFDM system two different kinds of special designed training symbols structures are utilized. However, both [5] and [6] have not considered the effect of phase noise. In [7], a partial pilot filling (PPF) compensation scheme is proposed, which uses constant pilot frequencies and is based on linear interpolation, and it has been proved to be an effective method to compensate the laser phase noise in CO-OFDM system. In [8], the orthogonal basis expansion (OBE) based approach is designed to mitigate the phase noise for PDM CO-OFDM but it does not considers the IQ imbalance when compensates the phase noise. Then [9] proposes a novel compensation method for Tx IQ imbalance as well as laser phase noise in which both two distortions are compensated by inserting two training symbols, but the transmission bit rate in [9] is limited and the method is used in CO-OFDM system.

In this paper, we design a novel pilot structure in the presence of channel distortion, Tx IQ imbalance and phase noise in PDM CO-OFDM system. This pilot structure includes two parts: the block-type pilot which is from [6] contains four training symbols in each polarization and it is inserted to estimate the channel distortion and IQ imbalance factors, while the comb-type pilot is some specific number of pilot subcarriers we utilize to estimate the phase noise. By using this pilot structure we can realize the independent estimation of the channel distortion and IQ imbalance factors as well as the effective estimation of the phase noise, then after estimation we can compensate the channel distortion, IQ imbalance and phase noise in sequence. Simulation results prove that the proposed method outperforms the conventional compensation method obviously for it can be applied to PDM CO-OFDM system both in low and high transmission bit rate and also significantly reduce the bit error rate (BER).

2. Theory deduction

Fig. 1 shows a typical schematic diagram of PDM CO-OFDM system. While considering all the linear transmission impairments, chromatic

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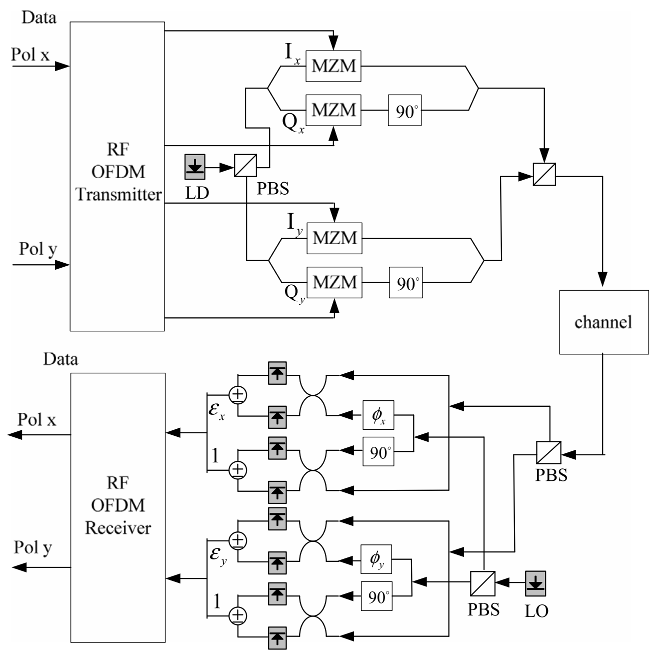

Fig. 1. Schematic diagram of PDM CO-OFDM system.

(CD), polarization-mode dispersion (PMD) in the optical fiber channel, IQ imbalance as well as laser phase noise, the received OFDM signal in frequency domain can be written as [10]:

$$\begin{pmatrix} R_x(k,i) \\ R_y(k,i) \end{pmatrix} = \begin{pmatrix} H_{xx}(k) & H_{yx}(k) \\ H_{xy}(k) & H_{yy}(k) \end{pmatrix} \begin{pmatrix} \Phi_x(i) & 0 \\ 0 & \Phi_y(i) \end{pmatrix} \begin{pmatrix} G_{1x} S_x(k,i) + G_{2x} \overline{S}_x^*(k,i) \\ G_{1y} S_y(k,i) + G_{2y} \overline{S}_y^*(k,i) \end{pmatrix} \tag{1}$$

Where

$$\overline{S}_x^*(k,i) = S_x^*(\mathrm{mod}((N-k),N),i), 0 \le k \le N-1$$
$$\overline{S}_y^*(k,i) = S_y^*(\mathrm{mod}((N-k),N),i), 0 \le k \le N-1,$$

$G_{1x} = \frac{1+\varepsilon_x e^{j\varphi_x}}{2}$, $G_{2x} = \frac{1-\varepsilon_x e^{j\varphi_x}}{2}$, $G_{1y} = \frac{1+\varepsilon_y e^{j\varphi_y}}{2}$, $G_{2y} = \frac{1-\varepsilon_y e^{j\varphi_y}}{2}$, i and k represent the ith symbol and kth subcarrier, $k \in [0, N-1]$ while N is the total number of OFDM subcarriers. $R_{x/y}(k,i)$ denotes the received signal while $S_{x/y}(k,i)$ and $\overline{S}_{x/y}^*(k,i)$ represent the transmitted signal and its mirror image conjugate. $H_{ab}(k)$ is the channel distortion of kth subcarrier from polarization state a to polarization state b and the channel symbol index is omitted for the optical channel varies slowly.

$\Phi_{x/y}(i) = e^{j\theta_{x/y}(i)}$ denotes phase noise while we only consider the common phase error (CPE) because when the phase noise is not too large the inter-carrier-interference (ICI) could be treated as additive Gaussian noise and the main impairment is caused by the CPE so we did not consider the ICI. $\phi_{x/y}$ and $\varepsilon_{x/y}$ represent the phase imbalance and amplitude imbalance while $G_{1x/y}$ and $G_{2x/y}$ denote IQ imbalance factors.

Block-type pilots $\begin{bmatrix} s_1 & s_1 & s_2 & s_2 \end{bmatrix}$ in polarization x and $\begin{bmatrix} s_1 & -s_1 & s_2 - s_2 \end{bmatrix}$ in polarization y are inserted at the beginning of the OFDM frame to compensate the channel distortion and IQ imbalance factor independently and the data of these pilots is set as the rule described in [6]. Then for the purpose of phase noise compensation L comb-type pilots are uniformly inserted in each OFDM block. The date satisfies: $S_{x/y}(k_l,i) = S_{x/y}^*(\mathrm{mod}(N-k_l,N),i)$, $(l = 0,1,\ldots,L-1)$, k_l denotes the position of the pilot subcarrier.

For the IQ imbalance factor satisfies $G_{1x/y} + G_{2x/y} = 1$, the first two received block-type pilots can be written as:

$$\begin{pmatrix} R_x(k,1) \\ R_y(k,1) \end{pmatrix} = \begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} \begin{pmatrix} s_1(k) \\ s_1(k) \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} R_x(k,2) \\ R_y(k,2) \end{pmatrix} = \begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} \begin{pmatrix} s_1(k) \\ -s_1(k) \end{pmatrix} \tag{3}$$

Define

$$\begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} = \begin{pmatrix} H_{xx}(k) & H_{yx}(k) \\ H_{xy}(k) & H_{yy}(k) \end{pmatrix} \begin{pmatrix} e^{j\theta_x(i)} & 0 \\ 0 & e^{j\theta_y(i)} \end{pmatrix} \tag{4}$$

Here we assume $\theta_{x/y}(i) = \theta_{x/y}, (i = 1,2,3,4)$ as the initial phase noise for the phase error between the adjacent symbols is little. Then, the channel distortion can be estimated as:

$$\begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} = \frac{1}{2s_1(k)} \begin{pmatrix} R_x(k,1) + R_x(k,2) & R_x(k,1) - R_x(k,2) \\ R_y(k,1) + R_y(k,2) & R_y(k,1) - R_y(k,2) \end{pmatrix} \tag{5}$$

The IQ imbalance factors can be estimated depends on the third and fourth block-type pilots. The received block-type pilots can be written as:

$$\begin{pmatrix} R_x(k,3) \\ R_y(k,3) \end{pmatrix} = \begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} \begin{pmatrix} A_x s_2(k) \\ A_y s_2(k) \end{pmatrix} \tag{6}$$

$$\begin{pmatrix} R_x(k,4) \\ R_y(k,4) \end{pmatrix} = \begin{pmatrix} H'_{xx}(k) & H'_{yx}(k) \\ H'_{xy}(k) & H'_{yy}(k) \end{pmatrix} \begin{pmatrix} A_x s_2(k) \\ A_y(-s_2(k)) \end{pmatrix} \tag{7}$$

Where $A_x = 1 - 2G_{2x}$, $A_y = 1 - 2G_{2y}$. Then we can get the IQ imbalance factors from (6) and (7):

$$\begin{cases} A_x = \dfrac{1}{2N} \displaystyle\sum_{k=0}^{N-1} \dfrac{s_x(k,1)}{s_x(k,3)} \left[\dfrac{R_x(k,3) + R_x(k,4)}{R_x(k,1) + R_x(k,2)} + \dfrac{R_y(k,3) + R_y(k,4)}{R_y(k,1) + R_y(k,2)} \right] \\ A_y = \dfrac{1}{2N} \displaystyle\sum_{k=0}^{N-1} \dfrac{s_y(k,1)}{s_y(k,3)} \left[\dfrac{R_x(k,3) - R_x(k,4)}{R_x(k,1) - R_x(k,2)} + \dfrac{R_y(k,3) - R_y(k,4)}{R_y(k,1) - R_y(k,2)} \right] \end{cases} \tag{8}$$

$$\begin{cases} G_{2x} = \dfrac{1 - A_x}{2}, & G_{1x} = 1 - G_{2x} \\ G_{2y} = \dfrac{1 - A_y}{2}, & G_{1y} = 1 - G_{2y} \end{cases} \tag{9}$$

From Eq. (5) as well as using the zero-force equalization [5], we can get the signal after channel equalization:

$$\begin{pmatrix} S'_x(k,i) \\ S'_y(k,i) \end{pmatrix} = \begin{pmatrix} H'_{xx} & H'_{yx} \\ H'_{xy} & H'_{yy} \end{pmatrix}^{-1} \begin{pmatrix} R_x(k,i) \\ R_y(k,i) \end{pmatrix} \tag{10}$$

As the initial phase has been removed with channel equalization, the signal after channel equalization can be written as:

$$\begin{pmatrix} S'_x(k,i) \\ S'_y(k,i) \end{pmatrix} = \begin{pmatrix} e^{j\Delta\theta_x(i)} 0 \\ 0 e^{j\Delta\theta_y(i)} \end{pmatrix} \begin{pmatrix} G_{1x} S_x(k,i) + G_{2x} \overline{S}_x^*(k,i) \\ G_{1y} S_y(k,i) + G_{2y} \overline{S}_y^*(k,i) \end{pmatrix} \tag{11}$$

Then we insert L comb-type pilot in certain position to estimate the phase noise and normally we take $L =$ 10 [8]. The phase difference can be expressed as:

$$e^{j\Delta\theta'_{x/y}(i)} = \frac{1}{L} \sum_{l=0}^{L-1} \frac{S'_{x/y}(k_l,i)}{S_{x/y}(k_l,i)}, \quad i = 5,6,\ldots,N_f + 4 \tag{12}$$

The transmitted symbol can be recovered with zero-force algorithm:

$$\hat{S}_x(k,i) = \frac{G_{1x}^* e^{-j\Delta\theta'_x(i)}}{|G_{1x}|^2 - |G_{2x}|^2} S'_x(k,i) - \frac{G_{2x} e^{j\Delta\theta'_x(i)}}{|G_{1x}|^2 - |G_{2x}|^2}{}_x \overline{S'_x}^*(k,i)$$
$$\hat{S}_y(k,i) = \frac{G_{1y}^* e^{-j\Delta\theta'_y(i)}}{|G_{1y}|^2 - |G_{2y}|^2} S'_y(k,i) - \frac{G_{2x/y} e^{j\Delta\theta'_y(i)}}{|G_{1y}|^2 - |G_{2y}|^2} \overline{S'_y}^*(k,i) \tag{13}$$

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