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Block Decision-Aided Laser Phase Noise Estimation for Coherent Optical OFDM Systems

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ABSTRACT

In this paper, we propose a block decision-aided (BL-DA) laser phase noise (LPN) estimation algorithm for coherent optical OFDM (CO-OFDM) systems. The OFDM symbols are divided into several blocks and the LPN estimation and compensation procedure is performed based on the decisions between these blocks. The proposed BL-DA algorithm can be applied for higher LPN estimation while at the same time ensuring a better estimation performance. Simulations are carried out in a 70.6 Gbit/s 16-QAM CO-OFDM system to verify the feasibility and efficiency of the BL-DA algorithm.

Keywords: *Coherent OFDM, laser phase noise, block decision-aided*

1. INTRODUCTION

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) has been an attractive technology for long-haul optical communication systems due to its high spectral efficiency and excellent tolerance to fiber chromatic dispersion (CD) and polarization mode dispersion (PMD) [1]. However, due to its longer symbol duration compared with a single carrier system, CO-OFDM is more sensitive to the laser phase noise (LPN).

Various approaches have been proposed to estimate and compensate for the LPN [2-4], which can be classified into two categories: data-aided and blind algorithms. However, the implementation complexity of blind algorithms is usually quite high. The data-aided algorithms include pilot-aided (PA) method based on the pilot subcarriers [3] and decision-aided (DA) method based on the decision of previous OFDM symbol [4]. The DA technique was initially proposed for carrier phase estimation in single carrier systems [5] and further extended for OFDM systems [4]. The conventional DA method in CO-OFDM estimates the common phase error (CPE) of current symbol by utilizing the decisions from the previous symbol. Based on this information, only one step of compensation and demodulation is required for each symbol. For the PA method, to achieve a better LPN estimation performance, more pilot subcarriers need to be inserted into the OFDM spectrum, which takes up useful bandwidth. For the conventional DA method, although the effective transmission bit rate can be improved compared with the PA method, DA shows less tolerance to the phase noise when the variance of LPN is large, due to the large laser linewidth of laser.

In this paper, a block decision-aided (BL-DA) algorithm is proposed to increase both the estimation accuracy and LPN tolerance, compared with the conventional DA method. Investigations of the performance improvement by increasing the number of blocks and the BER performance comparison between PA, DA and BL-DA are carried out through simulations.

2. SIGNAL MODEL

The n-th received time domain OFDM sample $\tilde{r}(n)$ with the appearance of carrier frequency offset (CFO) and LPN can be expressed as [6]

$$\tilde{r}(n) = \tilde{y}(n)e^{j(2\pi\epsilon n/N+\theta(n))} + \tilde{w}(n), n = 0, \cdots, N-1. \quad (1)$$

Here, ϵ is the CFO normalized by the subcarrier spacing f_0 and N is the size of Fast Fourier Transform (FFT). Term $\theta(n)$ is the LPN which is a Wiener process, modeled by

$$\theta(n) = \theta(n-1) + \nu(n) \quad (2)$$

where $\{\nu(n)\}$ is a set of independent and identically distributed, zero-mean Gaussian random variables, with

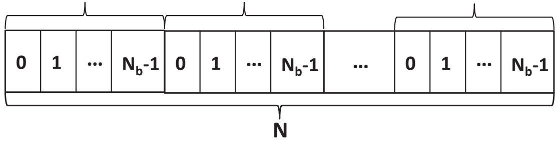


Fig. 1. Proposed block structure for one OFDM symbol.

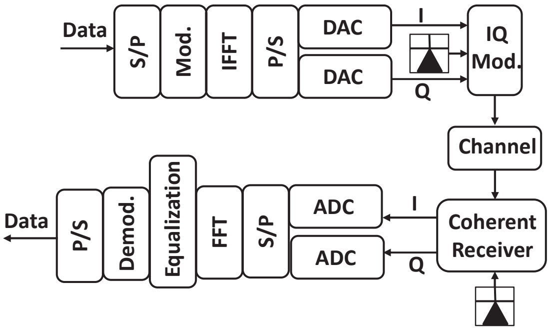


Fig. 2. The schematic structure of the CO-OFDM system (Mod: modulation, Demod: demodulation, S/P: serial to parallel, P/S: parallel to serial, DAC: digital to analog converter, ADC: analog to digital converter).

variance $\sigma_p^2 = 2\pi(2\Delta\nu)T_s$, where $\Delta\nu$ accounts for the linewidth of each laser and T_s is the sample time interval. Term $\tilde{w}(n)$ is the complex, additive, white, Gaussian noise (AWGN) with mean zero and variance σ^2. Note that $\{\tilde{\cdot}\}$ represents the complex signal. Term $\tilde{y}(n)$ is the n-th time domain output sample which can be expressed as

$$\tilde{y}(n) = \frac{1}{N}\sum_{k=-N/2}^{N/2-1}\tilde{X}(k)\tilde{H}(k)e^{j2\pi kn/N} \tag{3}$$

where $\tilde{X}(k)$ and $\tilde{H}(k)$ represent the transmitted signal and the channel transfer function on the k-th subcarrier in the frequency domain, respectively.

3. BLOCK DECISION-AIDED LASER PHASE NOISE ESTIMATION

Suppose the channel distortions including CD and PMD have been removed, and the CFO also has been compensated. Since σ_p^2 is determined by both the combined laser linewidth (CLW) and sample time interval T_s, for our experimental transmission system, the sample rate is 25 GSa/s and with a relatively small CLW, the σ_p^2 is quite small. Therefore, for the CO-OFDM system, we can assume the LPN is a constant within a certain block.

After the channel distortions are removed, the time domain received signal in (1) with the appearance of LPN and complex AWGN can be rewritten as

$$\tilde{r}_i(n) = \tilde{x}_i(n)e^{j\theta_i} + \tilde{w}_i(n) \tag{4}$$

where i represents the i-th block and we have $i = 1,2,\cdots L$, where L is the number of blocks in one OFDM symbol. The block length then can be obtained as $N_b = N/L$. The proposed block structure is shown in Fig. 1. After taking the N-point FFT, the received signal in frequency domain can be expressed as

$$\tilde{R}_i(k) = \tilde{X}_i(k)e^{j\theta_i} + \tilde{W}_i(k). \tag{5}$$

Since we regard the LPN in each block as a constant, after taking the DFT, the constant phase will not change. Similar with the conventional DA method in [2], we introduce a complex phasor V based on the decision statistics of the previous block, which is given by

$$V_i = \frac{1}{N_b}\sum_{k=0}^{N_b-1}\left|\tilde{D}_{i-1}(k)\right|^{-2}\tilde{R}_i(k)\tilde{D}_{i-1}^*(k) \tag{6}$$

where $\tilde{D}_{i-1}(k)$ is the receiver's decision for the k-th sample in the i-th block. Then the estimated LPN in each block can be obtained by taking the angle of V_i,

$$\hat{\theta}_i = \angle V_i. \tag{7}$$

Compared with the conventional DA method, where L equals to one and N_b is actually the FFT size, the proposed block DA algorithm can realize more accurate LPN estimation especially under the case of high laser linewidth. Moreover, the conventional DA method requires a preamble whose length is equal to the FFT size, which reduces the effective transmission bit rate. However, the proposed block DA algorithm needs the first block to be known whose length is only N_b which not only decreases the length of overhead but also achieves better LPN estimation performance.

4. SIMULATION RESULTS AND DISCUSSION

The CO-OFDM system is built by simulations using MATLAB. The transmitter and receiver block diagram of our CO-OFDM system is shown in Fig. 2. The original 70.6 Gbit/s data is modulated onto 384 subcarriers with 16-QAM modulation and transferred to the time domain by taking the 512-point IFFT. The other 128 subcarriers are zero-padded for over-sampling purpose. The number of total transmitted OFDM symbols is 64 and the length of cyclic prefix (CP) is 32 samples. The OFDM signal is transmitted with the sample rate of 25 GSa/s.

The investigation of the impact of the number of blocks on the BER performance is shown in Fig. 3. As can be seen in the figure, the BER performance is improved by increasing the number of blocks. This is because compared with the conventional DA method which uses the whole OFDM symbol to estimate the phase noise, the divided blocks of BL-DA method can fit

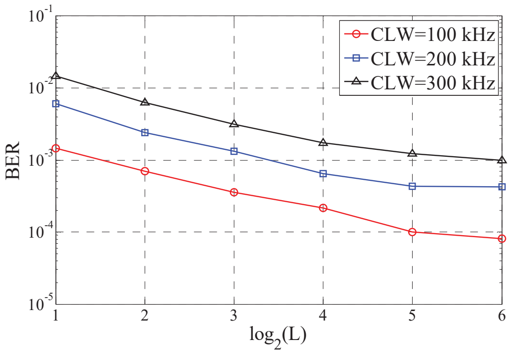
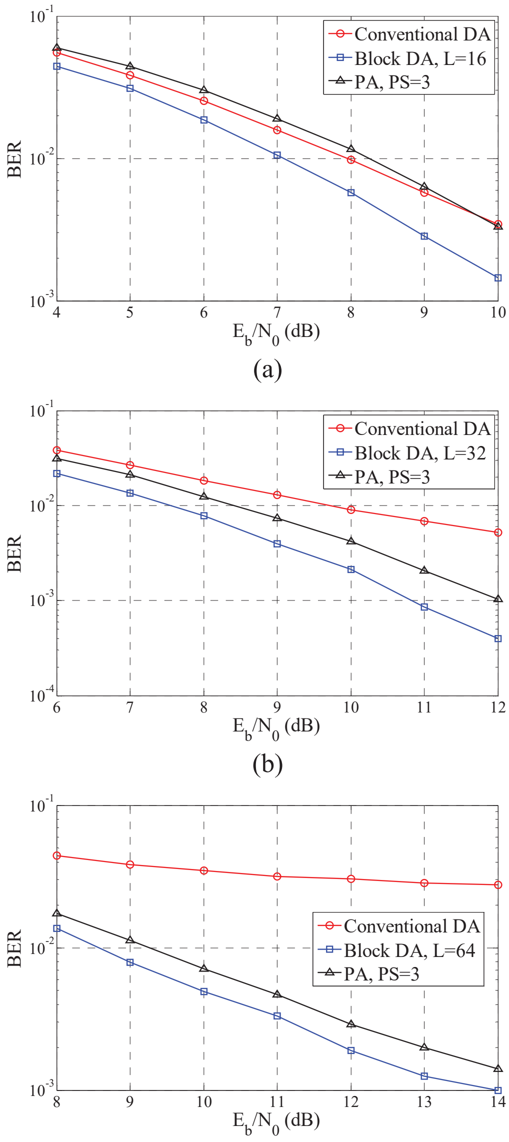


Fig. 3. BER versus $\log_2 L$ under various combined laser linewidths at E_b/N_0 of 15 dB.



(a)

(b)

(c)

Fig. 4. BER versus E_b/N_0 with the CLW of (a) 100 kHz; (b) 200 kHz; (c) 300 kHz.

the variation of LPN, and thus improve the BER performance. Moreover, with the increase of combined laser linewidth, the BER performance degrades correspondingly. Thus for real applications, in the case of low LPN, we can use a small number of blocks for estimation, while with high LPN, we can divide the OFDM symbol into more blocks to ensure the total BER performance.

Figure 4 shows the BER performance comparison between the conventional DA, PA and proposed block DA methods. For the PA algorithm, the number of pilot subcarriers (PS) inserted in the OFDM spectrum is 3. In this simulation, we use more blocks when the LPN is high. It can be seen in the figure that when the LPN is small, the conventional DA outperforms PA, however, when the CLW is 300 kHz, the BER of DA method is quite high, which is around one order higher than the PA method. This is because the DA method regards the LPN within a whole OFDM symbol as a constant, and thus for a high LPN, the noise variance is large, and the system performance degrades quickly. This illustrates that the DA method is not tolerant to high LPN. Besides, it is obvious in Fig. 4 that the proposed BL-DA method always performs the best even with higher laser phase noise, which verifies the feasibility, efficiency and superior estimation accuracy of the proposed BL-DA algorithm.

5. CONCLUSION

We proposed a block decision-aided LPN estimation algorithm by dividing the OFDM symbol into small blocks. BER performance comparison was carried out between the conventional DA, PA and proposed BL-DA methods. Simulation results show that the BL-DA algorithm not only has a better tolerance to higher LPN compared with conventional DA, but also can achieve a more accurate LPN estimation performance.

6. ACKNOWLEDGMENTS

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