Image Processing Based Common Phase Estimation for Coherent Optical Orthogonal Frequency Division Multiplexing System

Tianwai Bo[1], Lingchen Huang[1,2], Calvin Chun-Kit Chan[1]
1. Department of Information Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong SAR, China
2. Centre for Optical and Electromagnetic Research of Zhejiang University, Hangzhou, China
Author e-mail address: tianwai@ie.cuhk.edu.hk

Abstract: A novel common phase error estimation method based on image processing technique is proposed. Both numerical simulations and experiments prove its feasibility to compensate phase noise with improved spectral efficiency than the pilot-subcarrier aided method.

OCIS codes: (060.2330) Fiber optics communications; (060.1660) Coherent communications.

1. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) is a promising technique enabling next-generation terabit-per-second, bandwidth-variable elastic optical network [1]. It exhibits a superb tolerance to the chromatic dispersion and polarization mode dispersion, but is very susceptible to laser phase noise and fiber nonlinearity. In general, laser phase noise induces a common phase error (CPE) to each OFDM symbol, which severely degrades the system performance if it is not properly estimated and compensated. Conventional compensation method for CPE can be classified into two categories, namely analog approaches based on RF-pilot and digital approaches based on pilot subcarriers or blind estimation methods. Phase estimation using RF-pilot requires frequency guard bands and power overheads, thus reduces the spectral efficiency. Pilot subcarrier aided (PA) [2] is the most widely used CPE method, due to its simplicity and accuracy. Nevertheless, it occupies a relatively a large number of subcarriers, which also reduced the spectral efficiency. Other non-data-aided CPE methods are mostly dependent on modulation formats and require extensive computation.

In this paper, we propose a novel CPE method based on minimum bounding box (MBB) algorithm, which has been widely employed to solve the skew problem of scanned image in the area of computer vision [3]. The idea is based on the geometric shape of the constellation diagram in one OFDM symbol, which can be treated as a rotated rectangle for the case of square quadrature amplitude modulation (QAM) mapping, under the effect of common phase error. The area of its two-dimensional bounding box, is a function of the revolved angle, and has the minimum value when the rotation is accurately compensated. To eliminate the ambiguity, a quasi-pilot scheme is proposed by employing only two bits of a symbol on one pilot subcarrier, thus drastically reduces the requirement of the large number of pilot subcarriers used in the conventional PA method. We have compared our proposed method with the widely used PA method, via both numerical simulations and experiments. It is shown that our proposed scheme exhibits a comparable performance than the conventional PA method, at the expense of only two bits on one pilot subcarrier, proving its feasibility and much improved spectral efficiency.

2. Principles

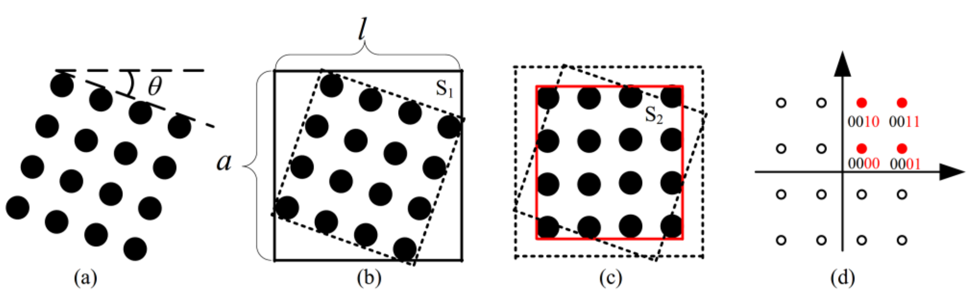

Fig. 1 (a)-(c) Principle of the proposed scheme (d) bit mapping scheme for the quasi-pilot subcarrier. All the symbols in this pilot subcarrier are modulated in the 1st quadrant, the last two bits (red) are for normal data modulation.

The laser linewidth characterizes the variance of random phase noise to each symbol in the time domain. After the coherent detection, OFDM demodulation and channel equalization, the phase noise induces a common rotation to all the subcarriers in one symbol. Here, we consider a 16-QAM mapping, as an example for illustration. If we view the constellation diagram as a graph, it can be regarded as a square with skew of an angle of θ, as shown in Fig. 1(a). In this way, the CPE of the coherent OFDM is formulated as a skew detection problem, which is a mature research area in image processing. Considering the computation complexity and the feasibility in implementation, we employ a straightforward approach to estimate the CPE, via minimizing the bounding box of the constellation.

Consider the constellation of a received OFDM symbol after channel estimation and equalization, the bounding box is defined as the minimum outer rectangle in horizontal orientation that can cover all the constellation points, as shown in Fig. 1(b). First, the received symbol is rotated by N test phases in the range of [0, π/2], in parallel. For each rotated symbol, the area of the bounding box s is calculated as

$$s(\varphi) = l \bullet a = \left\{\max\left[\mathrm{Re}\left(r \cdot e^{j\varphi_k}\right)\right] - \min\left[\mathrm{Re}\left(r \cdot e^{j\varphi_k}\right)\right]\right\} \bullet \left\{\max\left[\mathrm{Im}\left(r \cdot e^{j\varphi_k}\right)\right] - \min\left[\mathrm{Im}\left(r \cdot e^{j\varphi_k}\right)\right]\right\} \tag{1}$$

where r is the received symbols after channel equalization and φ_k is the k-th test phase, Re(⋅) and Im(⋅) represent the real and the imaginary parts of the complex number. l and a are respective lengths of the two sides of the bounding box, as illustrated in Fig. 1(b). The algorithm is based on calculating the area, s, covered by this bounding box under each test phase value (see Fig. 1(c)), which only requires very low computation complexity. The optimum estimated phase is determined by the test phase that minimizes the area s, i.e.

$$\hat{\theta} = \arg\min_{\varphi} \left\{ s(\varphi) \right\} \tag{2}$$

To eliminate the ambiguity, a pilot subcarrier is inserted. However, the absolute angle of the pilot is not needed, as the quadrant information is enough. The pilot subcarrier is modulated with only the complex symbols in the first quadrant of the constellation. The rest of the bits in the symbol of the subcarrier are still modulated with data, thus it is called as a quasi-pilot subcarrier, as illustrated in Fig. 1(d). After compensation, via the proposed minimum bounding box (MBB) algorithm, the quadrant of the pilot subcarrier is calculated and used for ambiguity elimination. As it will be shown later, one quasi-pilot is sufficient to dispel the uncertainty, thus the required overhead is quite small.

3. Numerical simulations

We first carried out numerical simulations to verify the feasibility of our proposed scheme. The CO-OFDM system used in our simulation had 256 subcarriers, 128 of them were modulated with data, with another 11 subcarriers as pilot subcarriers, for comparison. One more quasi-pilot subcarrier was inserted using the mapping method as described above. The sampling rate was 12 GSamples/s. The modulation formats were quadrature phase-shift keying (QPSK) and 16-QAM, which corresponded to a total bit rates of 12 Gbps and 24 Gbps, respectively. The linewidths of the laser used for signal generation and that of the the laser used as local oscillator were both 100 kHz. Both back-to-back and 1000-km transmission performance of were simulated.

Fig. 2(a) shows the bit error rates (BER) versus optical signal-to-noise ratio (OSNR) for QPSK and 16-QAM. The results showed a good match with the PA method. Linewidth tolerances of our proposed method MBB, together with the commonly used PA method were also simulated, at the required OSNR when the bit error rate was 10^{-3} in both cases. As shown in Fig. 2(b), our proposed MBB method has comparable performance than the PA method, with very small penalty.

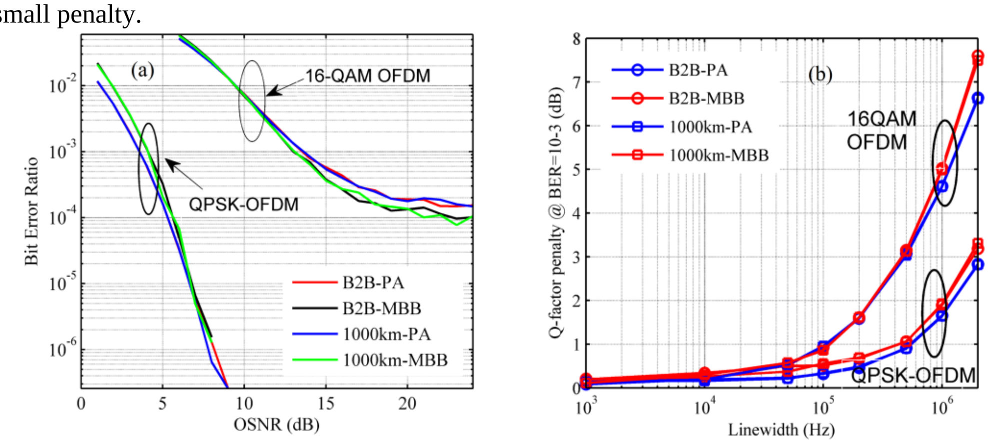

Fig. 2 Simulation results of (a) BER versus OSNR (b) Q-factor penalty w.r.t laser linewidth.

4. Experiments

Fig. 3 shows the experimental setup to verify our proposed CPE estimation scheme. A conventional CO-OFDM system with all the parameters identical to the simulation was implemented. The linewidths of the signal laser and the local oscillator were both 100 kHz, resulting in an equivalent linewidth of 200 kHz. The continuous wave was modulated with the OFDM signal, as described above, via an optical IQ modulator. The generated optical signal was first amplified by an Erbium doped fiber amplifier (EDFA), followed by a variable optical attenuator (VOA), and it was then loaded with ASE noise from another EDFA, to emulate different OSNR values. The optical signal was then fed into a recirculating loop, which comprised a segment of 70-km single mode fiber. The output signal was detected by a conventional coherent receiver for offline signal processing.

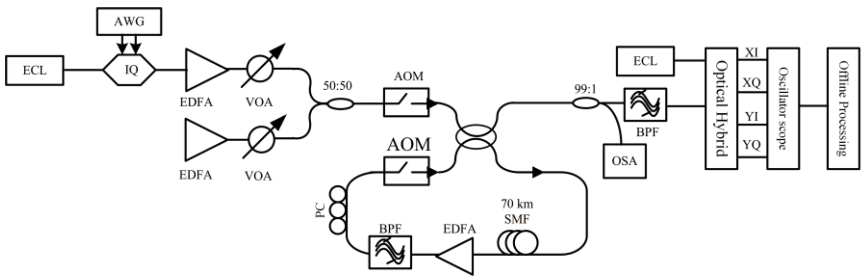

Fig. 3 Experimental Setup

Limited by the linewidth of laser we used, 16-QAM OFDM was only investigated in the back-to-back transmission, while both B2B and 1000 km transmission were conducted for QPSK OFDM. Fig. 4 (a) shows the BER performance for the B2B case for both PA and MBB phase noise estimation methods of QPSK-OFDM. The number of test phases here was 10. It was shown that our proposed method, using only one quasi-pilot subcarrier, had a comparable performance as the PA method, which employed 11 pilot subcarriers. In 16-QAM case, MBB has a better performance that PA, as shown in the inset of Fig. 4(a). As can be seen in Fig. 4 (c), PA has a residual phase error, while MBB behaves better due to more "square" property of 16 QAM. We further evaluated the transmission performance of both PA and MBB methods over 1000-km single mode fiber, and the results were shown in Fig. 4(b). The MBB method showed slight penalty, as compared to the PA method, but it only used two bits of one symbol (for QPSK, an entire symbol was used) in one quasi-pilot subcarrier, while eleven subcarriers were used in PA method, showing an obvious improvement in the spectral efficiency.

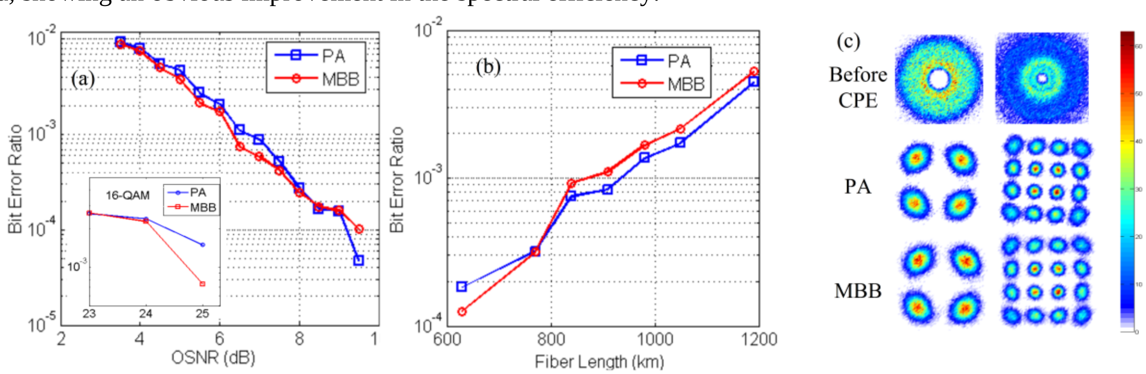

Fig. 4 Experimental results: BER performance of (a) back-to-back transmission (b) 1000-km fiber transmission, using PA and MBB (c) Constellation diagrams for QPSK and 16QAM OFDM signal before and after CPE correction using PA and MBB.

Summary

In this paper, we have proposed a novel CPE estimation method based on MBB, which is a common image processing technique. It has been proved, via numerical simulations and experiments, that it has comparable performance than the commonly used PA method, with a substantial improvement in spectral efficiency.

References

[1] S. Chandrasekhar, X. Liu, B. Zhu, and D. W. Peckham, ECOC 2009.
[2] X. Yi, W. Shieh, and Y. Tang, "Phase estimation for coherent optical OFDM," IEEE Photonics Technol. Lett. 19(12), 919–921 (2007).
[3] Sarfraz, M.; Rasheed, Z., "Skew Estimation and Correction of Text Using Bounding Box," Proceedings of Computer Graphics, Imaging and Visualization, (CGIV), pp.259-264, 2008.