Common Phase Estimation in Coherent OFDM System Using Image Processing Technique

Tianwai Bo, *Student Member, IEEE*, Lingchen Huang, and Chun-Kit Chan, *Senior Member, IEEE*

***Abstract*— In a coherent orthogonal frequency division multiplexing system, the possible rotation of the rectangular signal constellation, due to common phase error, is shown to be effectively compensated by applying an skew compensation technique adopted in image processing area. We further propose an improved technique to further reduce the complexity of the algorithm and investigate the effect of the number of required test phases, via numerical simulations. The proposed improved algorithm is also compared with the conventional blind phase searching algorithm. It is shown that by employing only two bits of overhead, it can achieve a comparable performance to that of the traditional pilot aided method.**

***Index Terms*— Coherent transmission, carrier phase recovery.**

I. 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 chromatic dispersion and polarization mode dispersion, but is very susceptible to laser phase noise due to its relatively long symbol duration. In general, laser phase noise introduces two effects on the optical OFDM signal, consisting of a linear part, called common phase error (CPE), and a nonlinear part, called inter-carrier interference (ICI) [4]. The phase noise severely degrades the system performance, and thus it is highly desirable to carefully estimate and compensate it.

There have been various reported approaches on how to compensate the common phase error in coherent optical systems. Conventional compensation methods can be classified into two categories, namely analog approaches based on RF-pilots and digital approaches based on pilot sub-carriers or blind estimation methods. Phase estimation using RF-pilot incorporates a carrier inserted at the OFDM spectrum and the carrier tone is extracted at the receiver for carrier recovery [2], [3]. It requires frequency guard bands and power overheads, thus reduces the spectral efficiency. Digital approaches include pilot aided (PA) methods [4] and blind methods [5]. PA is the most widely used CPE compensation method, due to its inherent simplicity and accuracy. Nevertheless, it occupies a relatively large number of subcarriers, which also reduces the spectral efficiency. Blind method does not need additional overhead but needs time to converge and usually has the cycle slip problem [4], which affects the laser phase tolerance, as well.

In [6], we have recently proposed a novel CPE compensation method based on finding the bounding box with minimum area (MBB), which has been widely employed to solve the skew problem of scanned images in the area of computer vision [7], [8]. The bounding box is the rectangle with the smallest area in the upright direction, covering all the pixels of a two-dimensional graph. The idea is based on the fact that the geometric shape of the constellation diagram of one OFDM symbol 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 inherent ambiguity of square constellation, 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, as used in the conventional PA method. We have compared our proposed method with the widely used PA method, via both numerical simulations and experiments. The results show 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.

In this letter, we further extend the investigation of [6], by proposing a complexity-reduced improvement to the MBB algorithm. The effect and computation complexity of the number of test phases in improved MBB algorithm are investigated. Moreover, we extend the signal modulation format considered from quadrature phase-shift keying (QPSK) to 16-QAM, under back-to-back and long-haul transmissions. The results are compared with the blind phase searching algorithm. In general, our proposed phase estimation method shows good tolerance to laser phase noise and enjoys a much improved spectral efficiency than the conventional pilot aided CPE estimation methods.

II. Principle

The laser linewidth characterizes the variance of random phase noise to each symbol in the time domain. After the

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T. Bo and C.-K. Chan are with the Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong (e-mail: bt012@ie.cuhk.edu.hk; ckchan@ie.cuhk.edu.hk).

L. Huang is with the Center for Optical and Electromagnetic Research, Zhejiang University, Hangzhou 310027, China (e-mail: huanglingchen@zju.edu.cn).

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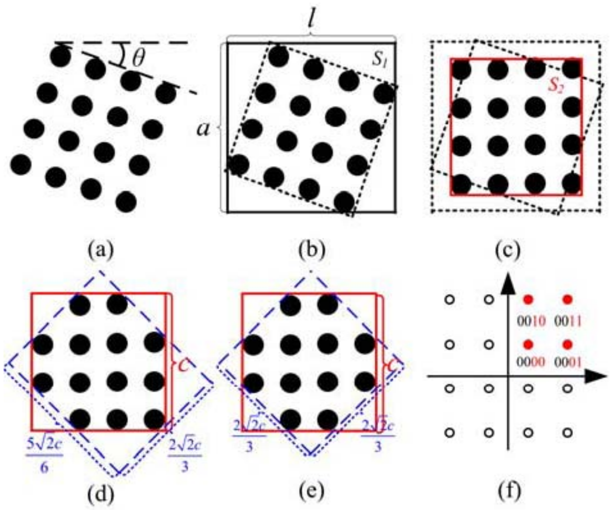

Fig. 1. Principles of using MBB to estimate the common phase error. (a) Constellation diagram of the received block. (b) The outer bounding box. (c) The minimum bounding box (red) of the original constellation diagram. (d) The case with three missing outer points. (e) The case with four missing outer points. (f) Coding method of our proposed quasi-pilot.

coherent detection and conventional demodulation procedures in a CO-OFDM system, there remains the phase noise induced common rotation to all the subcarriers in one OFDM symbol [4]. Here, we consider a 16-QAM mapping, as an example for illustration. If we view the constellation diagram as a graph in the two-dimensional plane, determined by in-phase (I) and quadrature (Q) components, 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 estimation of the coherent OFDM is formulated as a skew detection problem, which has been a matured research area in image processing [8]. Considering the computation complexity and the feasibility in implementation, we employ a straightforward approach to estimate the CPE, via minimizing the area of the bounding box of the signal constellation. Given 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 block of 16-QAM samples in the received OFDM symbol is rotated by N test phases, in the range of $(0, \pi/2]$, in parallel. For each rotated block, the area of the bounding box s is calculated as,

$$\begin{aligned} s(\varphi_k) &= l \cdot a \\ &= \left\{\max\left[\mathrm{Re}\left(r \cdot e^{j\varphi_k}\right)\right] - \min\left[\mathrm{Re}\left(r \cdot e^{j\varphi_k}\right)\right]\right\} \\ &\quad \cdot \left\{\max\left[\mathrm{Im}\left(r \cdot e^{j\varphi_k}\right)\right] - \min\left[\mathrm{Im}\left(r \cdot e^{j\varphi_k}\right)\right]\right\} \end{aligned} \quad (1)$$

where r is the received samples after channel equalization and φ_k is the k-th test phase. $\mathrm{Re}(\cdot)$ and $\mathrm{Im}(\cdot)$ represent the real and the imaginary parts of the complex number. l and a are the 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 (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.

$$\hat{\theta} = \arg\min_{\varphi} \{s(\varphi)\} \quad (2)$$

Note that the algorithm can also be applied to 32-QAM or 128-QAM mapping with their minimum areas of the bounding box occur at the upright direction, as well. To eliminate the ambiguity induced by the square constellation diagram, a pilot subcarrier is inserted. However, the absolute angle of the pilot is not needed, as the quadrant information is enough to eliminate the ambiguity. Here we propose a new design of the pilot subcarrier. One pilot subcarrier is modulated with only complex symbols in the first quadrant of the constellation, so as to serve as the indicator of the quadrant. For example, if the modulation data format is 16-QAM, the pilot subcarrier is modulated with symbols in the first quadrant of the constellation, as shown in Fig. 1(f). This quadrant indicator occupies only the first two bits of the pilot subcarrier, and thus the other two bits on the pilot subcarrier can still be used to carry data. It is thus named as a quasi-pilot subcarrier. After compensation, via the proposed algorithm, the quadrant of the pilot subcarrier is checked and used for ambiguity elimination. As will be shown later, one quasi-pilot is sufficient to dispel the uncertainty, thus the required overhead is quite small.

Besides, in case of the possible absence of the outermost symbols in the constellation, the proposed MBB algorithm can still correctly estimate the CPE. As depicted in Fig. 1(d), even when three corner symbols are absent, the area of the correct bounding box in red (c^2) is still smaller than the blue one ($10c^2/9$). However, for the case of missing all four corner symbols (see Fig. 1(e)), the area of the red bounding box is larger than that of the blue one ($8c^2/9$), thus estimation error may occur. This problem can be alleviated by increasing the number of subcarriers in one OFDM symbol.

III. Numerical Simulations

To extend the work reported in [6], we have further carried out numerical simulations to investigate the effect of the number of test phases (B), in the proposed technique, compared with the number of pilot subcarriers with identical performance, in a CO-OFDM system. In our simulation, 128000 16-QAM symbols were loaded onto 128 subcarriers. 20 pilot subcarriers were equally distributed among these data subcarriers for CPE estimation. One more quasi-pilot subcarrier was inserted using the mapping method, as described above for CPE estimation using MBB method. All the pilot subcarriers and the quasi-pilot used were normalized to have equal average power as the data subcarriers. The IFFT size was 256 with the other subcarriers padded to be zeros. The generated data was digitally sampled at a rate of 12 GSample/s. The length of the cyclic prefix was 12.5% of total subcarriers, thus the net data rate is ~21.4 Gb/s. The linewidths of the laser used for signal generation and that of the laser used as local oscillator were both 100 kHz, emulated under the model of Wiener process.

Fig. 2 shows that the bit error rate (BER) versus the number of test phases (B) used in the CPE processing. The optical

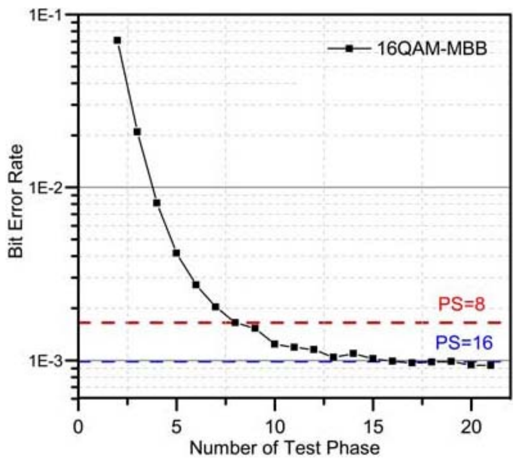

Fig. 2. Simulation results: BER versus the number of test phases B under the proposed MBB algorithm. OSNR=13 dB. PS is the number of pilot subcarriers under the PA method.

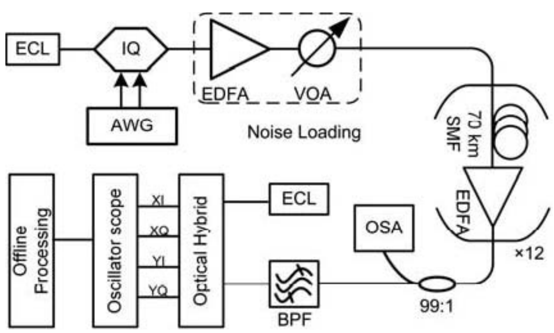

Fig. 3. Experimental setup. ECL: external cavity laser; AWG: arbitrary waveform generator; VOA: variable optical attenuator; OSA: optical spectrum analyzer; BPF: band pass filter.

signal-to-noise ratio (OSNR) was set to be 13 dB, which corresponded to a BER of 10^{-3} when no laser phase noise is loaded in our simulation system. As shown, 8 and 15 test phases had comparable performance as the cases of 8 and 16 pilot subcarriers (PS), respectively. Note that the increase in the test phase only increased the computation complexity of offline processing. The total overhead in each OFDM symbol was only 2 bits (one half symbol for a 16-QAM signal). Compared with the cases of 8 or 16 pilot symbols when PA method was used, the overhead of the proposed MBB algorithm was reduced by 93.75% and 96.88%, respectively.

IV. Experiments

Fig. 3 shows the experimental setup to verify our proposed CPE estimation scheme using MBB algorithm. A conventional CO-OFDM system with all the parameters identical to the simulation was implemented. Two Emcore tunable lasers were used as the signal laser and the local oscillator, with equal linewidth of ~100 kHz, resulting in an equivalent linewidth of 200 kHz. The radio-frequency (RF) OFDM signal was generated by an arbitrary waveform generator (Tektronix 7122C) with a sampling rate of 12 GSample/s. The continuous wave from the signal laser was then modulated with the RF OFDM signal, as described above, via an optical IQ modulator. The generated optical OFDM signal was first amplified by

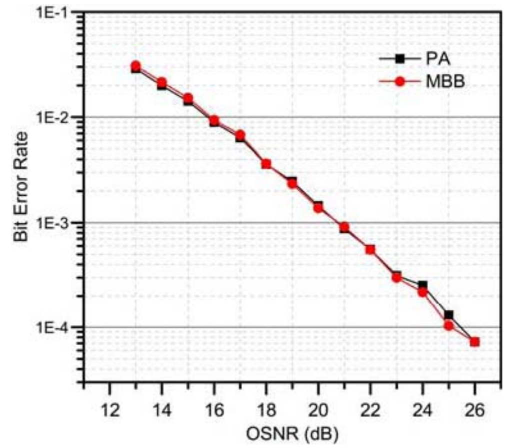

Fig. 4. B2B BER versus OSNR, under the PA method and the MBB method.

an Erbium doped fiber amplifier (EDFA), followed by a variable optical attenuator (VOA), so as 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, followed by an EDFA. The received optical signal was detected by a conventional coherent optical receiver. The electrical signal was then sampled by a real-time oscilloscope (Tektronix 72004B) at a sampling rate of 50 GSample/s for offline digital signal processing. Conventional OFDM synchronization and frequency offset compensation method were employed.

First, we investigated the BER of the demodulated OFDM signal under the proposed MBB algorithm and the conventional PA method, at different OSNR values, in back-to-back (B2B) transmission. 16 pilot subcarriers were employed in the PA method. The number of test phases used in the MBB method was 15. These two parameters were used hereafter. As shown in Fig. 4, the MBB scheme had a comparable performance as the PA method.

On the other hand, it is obvious that the symbols located at the inner part of the signal constellation has no influence on the characterization of the outer bounding box, thus can be removed to further reduce the computation complexity. Here, we define a clipping region, which corresponds to the circular area with a radius r from the center of the I-Q plane. The samples falling inside this clipping region will be omitted in the computation for the bounding box under the MBB algorithm. Fig. 5 shows the Q-factor penalty and the processing-ratio at an OSNR of 25 dB versus the clipping region radius r, varying from 0 to 4.2, where the processing-ratio is defined as the ratio of the number of samples involved in MBB processing and the number of total OFDM symbols. It was shown that as long as the radius was less than ~3.8, the BER performance was not affected. When the radius for clipping was 3.8, only 25% of the samples were used, and the respective induced Q-factor penalty was less than 0.1 dB. In practical implementation, a rectangular clipping area is more preferred, as it would be more hardware efficient to use comparators to process the clipping.

To further investigate the tolerance of the proposed MBB method against fiber nonlinearity, a long haul

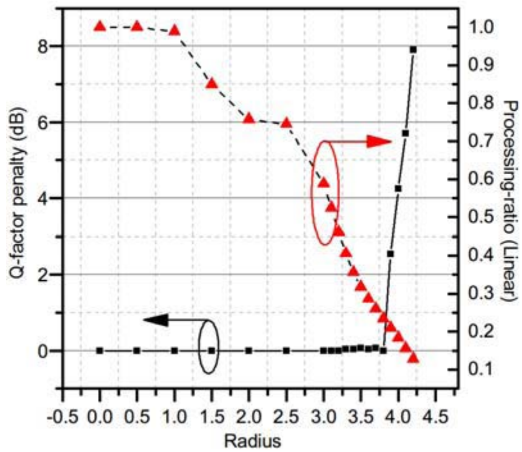

Fig. 5. Q-factor penalty when clipping with different radius r. OSNR=25 dB.

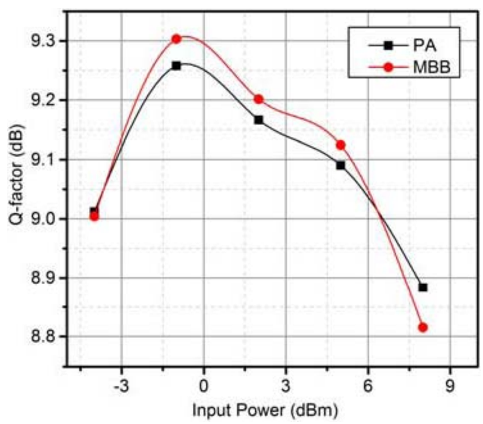

Fig. 6. Q factors versus input power with PA method and MBB method in 840-km single mode fiber transmission.

TABLE I

HARDWARE COMPLEXITY COMPARISON

	Multiplexers	Adders	Comparators	Decisions
BPS	*6MB+4M*	*6MB-B+2M+2*	*MB*	*MB+M*
MBB	*4MB+4M+B*	*2MB+2B+2M*	*4MB+B*	*0*

transmission experiment was conducted. As seen in Fig. 3, a recirculation loop with 12 spans was used to emulate 840-km single mode fiber transmission. The input power of the CO-OFDM signal was altered from −4 dBm to +7 dBm, in a step of 3 dB. The Q factors were calculated, using both PA and MBB methods, from 50000 OFDM packets at each input power value. Fig. 6 shows that MBB method had 0.05 dB performance increase than PA method at the optimum input power of −1 dBm. Their performance was comparable as well.

V. COMPUTATION COMPLEXITY

In general, conventional PA method had the least complexity, as it only calculated the phase average among all the pilot subcarriers. For example, if there were N pilot subcarriers, only 2^*N real adders and 2 real multiplexers were needed to estimate CPE in the PA method. Nevertheless, our proposed MBB method used a non-data aided approach to achieve comparable performance and much increased spectral efficiency than the conventional PA method, but at an expense of increased computation complexity. Here, we compared MBB method with blind phase searching (BPS) algorithm [9], [10], in terms of computation complexity, as they had similar algorithm design and hardware implementation. BPS is commonly used in single carrier and is assumed to have M symbols in one block and B test phases. M-QAM system and the carrier phase is estimated symbol by symbol. In CO-OFDM, CPE is processed in frequency domain and all the samples in one OFDM symbol share one common phase, thus it is processed block by block.

As shown in Table I, our proposed MBB method uses fewer real multiplexers and adders than BPS method without any decisions, though more comparators are required. If only the samples with the outermost symbols are considered in calculating the outer bounding box, M can be much smaller, thus the computation complexity can be further reduced.

VI. SUMMARY

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 gives substantial improvement in spectral efficiency and comparable performance over the conventional PA method.

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