Common Phase Error Estimation for Coherent Optical OFDM System Using Best-fit Bounding Box

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Abstract— **A new spectral-efficient image processing based scheme is proposed to blindly estimate the common phase error of coherent optical orthogonal frequency division multiplexing system. The scheme provides new perspective for compensating laser phase noise effect through simple image processing techniques used in computer vision. It shows comparable performance with conventional pilot aided method but much improved spectral efficiency.**

Keywords—laser phase noise, coherent transmission

I. Introduction

Coherent optical orthogonal frequency division multiplexing (CO-OFDM) is a promising technique enabling next-generation terabit-per-second, bandwidth-variable elastic optical networks. It exhibits a superb tolerance to the chromatic dispersion and polarization mode dispersion, but is very susceptible to laser phase noise, which severely degrades its system performance. Therefore, it is crucial to perform phase noise estimation and compensation in CO-OFDM systems.

In general, the phase noise effect in CO-OFDM systems comprises the common phase error (CPE) and the inter-carrier interference (ICI) [1]. Various CPE compensation schemes have recently been reported. The most widely used method is called pilot aided (PA) approach [1], owing to its inherent good simplicity and high accuracy. Nevertheless, it occupies a relatively large number of subcarriers, and thus reduces the spectral efficiency. Blind methods do not need additional overhead but usually suffer from cycle clip problem and are susceptible to laser phase noise.

The constellation diagram of all the quadrature amplitude multiplexing (QAM) points in one OFDM symbol can be treated as a planar graph over an I-Q plane. This provides a possibility that image processing methods may be feasible and effective to process the digital signal. In the presence of CPE, the constellation diagram of an OFDM symbol may be skewed. In our recent work [2], we reported our first proposal of adopting the technique, named as MBB, so as to search for a bounding box enclosing all the QAM points on the I-Q plane in one OFDM symbol, with the minimum box area. With blind phase searching, the retrieved orientation of the minimum bounding box accurately implies the skew of the constellation diagram, induced by CPE. Hence, the CPE can be accurately compensated. This MBB technique has been widely employed to solve the skew problem of scanned image in the area of computer vision. Verified by numerical simulations and experiments, it has been shown that the MBB method achieved comparable performance as the commonly used PA method, with a drastically reduced overhead in the spectrum.

In this paper, we propose a new geometric method to search for the minimum bounding box, which is named as best-fit bounding box (BBB) algorithm. The best-fit bounding box is defined as the rectangle covering all the constellation points with the minimum area, which is not limited to the horizontal or vertical direction. Based on the convex hull of the constellation points, the optimum best-fit bounding box can be found through the rotating calipers algorithm. Compared with the MBB method, there is no need to have blind phase searching, and does not need any branches of rotation of the constellation points. Therefore, the computation complexity is further reduced and the accuracy is increased. Besides, at most one subcarrier is required, thus have much improved spectral efficiency as compared with the conventional PA method.

II. Principles

For the received OFDM signal in QAM format, it is assumed that perfect synchronization and compensation of carrier frequency offset are first performed. The received complex symbols after fast Fourier transform (FFT) is then converted into a set of points in the Cartesian coordinates, with x- and y- coordinates being the real and the imaginary parts of the complex symbols, respectively. Fig. 1(a) shows the graph of the scattered points over the I-Q plane. Laser phase noise induced CPE is clearly noticed in form of the rotation of all the constellation points. The estimation of CPE can be formulated as finding the best-fit bounding box of these scattered points, such that the CPE corrupted constellation points can be easily rotated back to the horizontal and the vertical directions.

Then the convex hull of the points set is calculated. The convex hull of a set X in mathematics is defined as the smallest convex set that contains X. In computation geometry, the two dimensional (2D) convex hull of a finite point set S is the smallest 2D convex polygon that contains S. For instance, the points connected by red line in Fig. 1(b) are the corresponding convex hull of the set of received points. It has been proved [3] that the smallest enclosing rectangle of a polygon has a side collinear with one of the edges of its convex hull. Then rotating calipers algorithm [4] is used to find the best-fit bounding box.

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Each edge of the convex hull is gone through and rotated among the points of convex hull, such that the edge is along a major axis, say x-axis. The axis-parallel bounding box can be obtained by getting the maximum and the minimum point in the direction of remaining edges, as illustrated in Fig. 1(c) and Fig. 1(d). The area of the bounding box is calculated for each candidate edge in the convex hull. After traversing all the edges, the minimum area is selected and the slope angle of the corresponding edge is the estimated CPE angle. Note again that only the points in the hull are involved in the rotation.

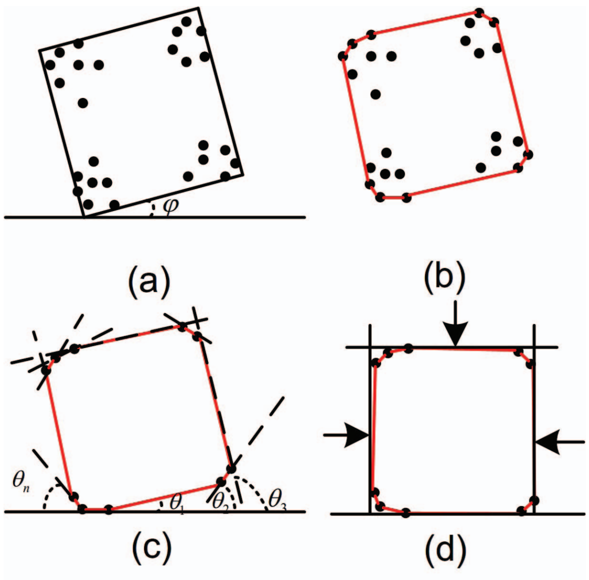

Fig. 1 Illustration of using convex hull and the rotating caliper algorithm to obtain the best-fit bounding box of a set of points.

Compared with the previously proposed MBB [2] method, the proposed BBB algorithm has reduced computation complexity and increased accuracy. In the MBB algorithm, a resolution has to be defined first, based on the modulation formats of mapping, to determine a set of test phases. For each test phase, all the constellation points are rotated and the bounding box area at this test phase is calculated. It requires extensive hardware resources in real implementation. However, in BBB algorithm, only the points in the convex hull are involved in the computation, thus the requirements for the real adders and multiplexers can be largely reduced. Meanwhile, the total number of rotation is determined by the number of edges of the convex hull, which is also a small number, according to the limited number of total points in the convex hull. The computation complexity of calculation the convex hull can be reduced as low as $O(n*\log(n))$ theoretically, where n is the total number of points. Therefore, only the outmost points in the constellation will be involved in the convex hull. The computation complexity of the rotating calipers algorithm is $O(n)$. Another benefit is that BBB can always enjoy a best-fit bounding box, as there is no resolution limit, thus it can achieve best accuracy of the MBB method, which can be seen in the following investigation.

However, similar to the MBB method, there exists the ambiguity problem. Here, we will use the same ambiguity elimination method, as that adopted in the MBB method [2], by inserting a pilot subcarrier carrying the quadrant information. The pilot subcarrier is modulated with only the complex symbols in the first quadrant of the constellation. For example, if the modulation format of data is 16-QAM, the pilot subcarrier is modulated with symbols from {1+1j, 1+3j, 3+1j, 3+3j}. To support this, the coding scheme can be modified by the first two bits being the indicator of quadrant, as shown in Fig. 2(a) and (b). Therefore, the pilot subcarrier can still carry some data, as only two bits are used for the quadrant information in case of 16-QAM. This pilot subcarrier is labelled as quasi-pilot subcarrier. After compensation, via the proposed best-fitting bounding box algorithm, the quadrant of the pilot subcarrier is checked and used for ambiguity elimination.

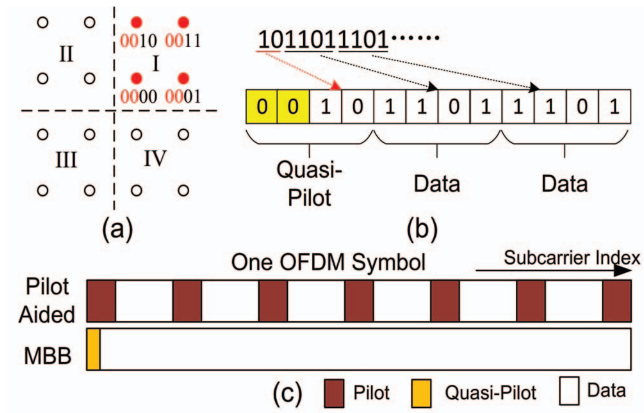

Fig. 2 (a) Quasi-pilots modulated in the first quadrant (b) Bit mapping of the quasi-pilot and normal data. (c) Spectral efficiency of conventional PA method and the proposed BBB method

III. NUMERICAL SIMULATIONS AND EXPERIMENTS

First we investigated the accuracy of the proposed BBB method, via numerical simulations. A typical CO-OFDM system was simulated and the simulation parameters were kept consistent with those adopted in our previous work of MBB method2. The optical-to-signal ratio (OSNR) at the coherent receiver was set to be 13.5 dB, and the modulation format was 16QAM-OFDM. As shown in Fig. 3, not like the MBB algorithm, the bit-error-rate (BER) performance under the BBB algorithm was not limited by the pre-defined resolution or the test phases. Moreover, the BBB algorithm exhibited similar BER performance, as that of MBB method with about 20 test phases. On the other hand, we compared the OSNR penalties at BER=1E-3, for both QPSK-OFDM and 16QAM systems, under different laser linewidths, when CPE estimation methods of pilot aided (PA), MBB and BBB were adopted. As depicted in Fig. 4, the OSNR penalty differences between these three CPE mitigation methods were negligible.

We then carried out a confirmatory back-to-back experiment for a 16QAM-CO-OFDM system, as in Fig. 5, with a combined laser linewidth of ~200 kHz. The sampling rate at arbitrary waveform generator (AWG) was 12 GSample/s. 128 of 256 subcarriers were modulated with data, and 16 pilot-aided carriers were inserted and equally distributed among the by an EDFA were used to emulate different OSNR values from

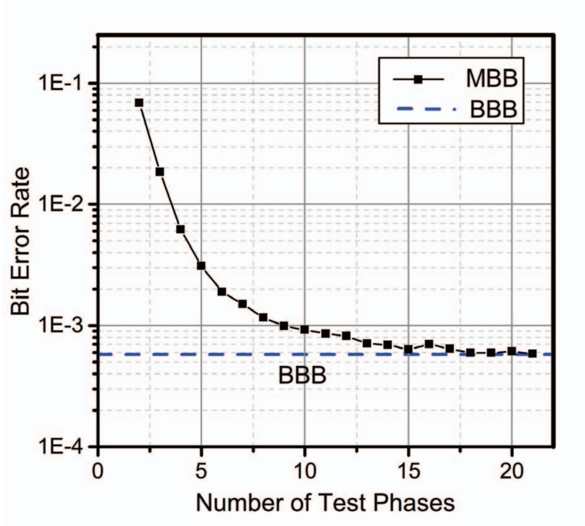

Fig. 3 Bit error rate versus number of test phase in MBB algorithm and bit error rate when BBB is used. OSNR=13.5 dB

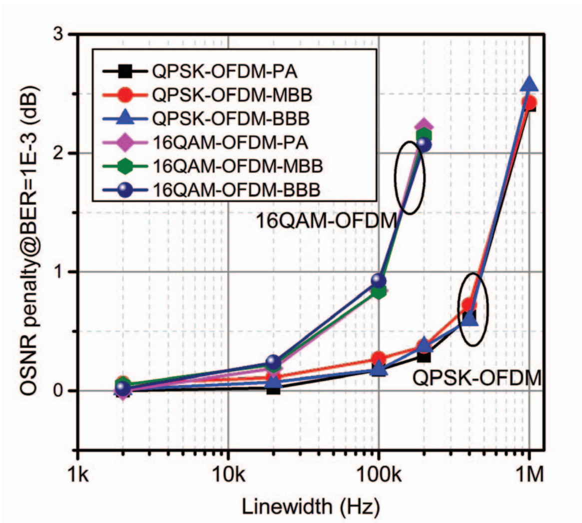

Fig. 4 Laser linewidth tolerance for PA, MBB, and BBB for both QPSK- and 16QAM-OFDM

13 dB to 23 dB. The optical OFDM signal was detected by a typical coherent received and the converted RF signal was sampled and stored via a real-time oscilloscope with a sampling rate of 50 GSample/s. Conventional digital signal processing techniques were performed for synchronization, frequency offset compensation and channel estimation. Fig. 6 shows the BER performances versus OSNR, under different CPE estimation methods. The number of test phases used in MBB method was 10 and 20. It was noticed that our proposed BBB method exhibited a comparable performance as the PA method and the MBB method with 20 test phases. An obvious improvement could be observed than MBB with 10 test-phase case. With the same spectral efficiency as in the MBB method, the BBB method also had much reduced complexity. The sizes of convex hull for the 128 subcarriers in each OFDM symbol have a mean value of 12.87 with a standard deviation of 1.90. Therefore, the number of complex multiplexers is reduced by a factor of ~10, indicating a significant reduce in complexity.

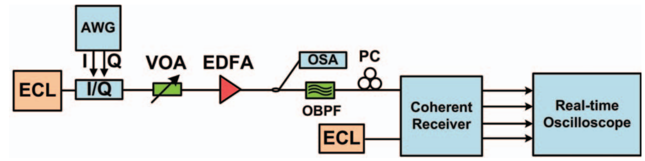

Fig. 5 Experimental setup

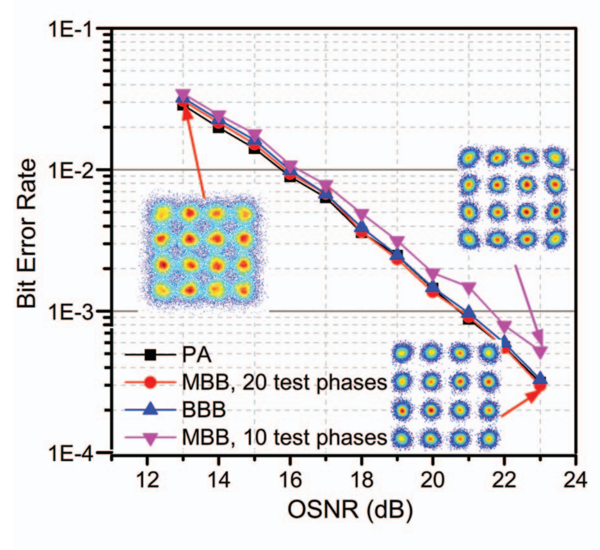

Fig. 6 BER result for PA, MBB and BBB

IV. Summary

We have proposed a novel CPE estimation method based on finding the best-fit bounding box of the constellation diagram. It has comparable performance as the commonly used PA method, and with a substantial improvement in spectral efficiency. Compared with the previously proposed MBB algorithm, its computation complexity is largely reduced.

Acknowledgement

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References

[1] X. Yi, et al., "Phase estimation for coherent optical OFDM", IEEE PTL., vol. 19, no. 12, p. 919-921, 2007.

[2] T. Bo, et al., "Image processing based common phase estimation for coherent optical orthogonal frequency division multiplexing system," OFC 2015, W1E.8.

[3] H. Freeman et al., "Determining the minimum-area encasing rectangle for an arbitrary closed curve," Commun. ACM, vol. 18, no. 7, pp. 409–413, Jul. 1975.

[4] G. Toussaint, "Solving geometric problems with the rotating calipers," in IEEE MELECON, 1983, pp. 10–02.