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Common Phase Estimation in Coherent Optical OFDM System Using Image Processing Technique

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Abstract

In a coherent OFDM system, the possible rotation of the rectangular signal constellation, due to common phase error, is shown to be effectively compensated by applying a 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.

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1. Main text

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

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(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 a given 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.

2. Principle

The laser linewidth characterizes the variance of random phase noise to each symbol in the time domain. After the coherent detection and conventional demodulation procedures of 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,

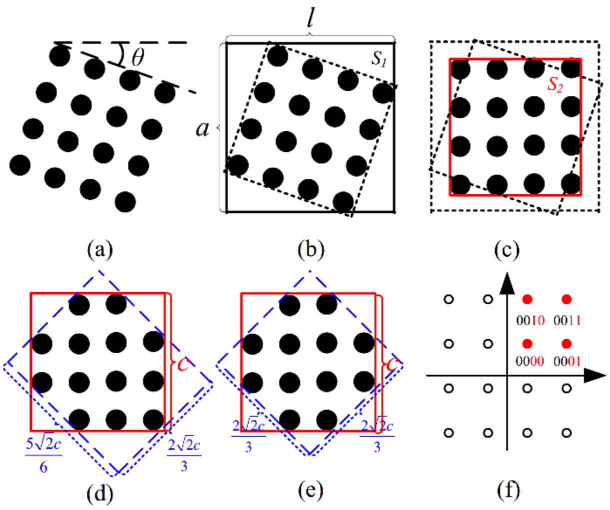

Fig. 1. . Principles of using MBB to estimate the common phase error. (a) Constellation diagram of the received block. (b) The outer bounding box. (c) The minimum bounding box (red) of the original constellation diagram. (d) The case with three missing outer points. (e) The case with four missing outer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

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

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.

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

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 of {1+*j*, 1+3*j*, 3+1*j*, 3+3*j*} 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. At the receiver, it only knows the pilot symbol should be in the first quadrant. After compensation, via the proposed minimum bounding box (MBB) 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.

3. 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 l 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 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.

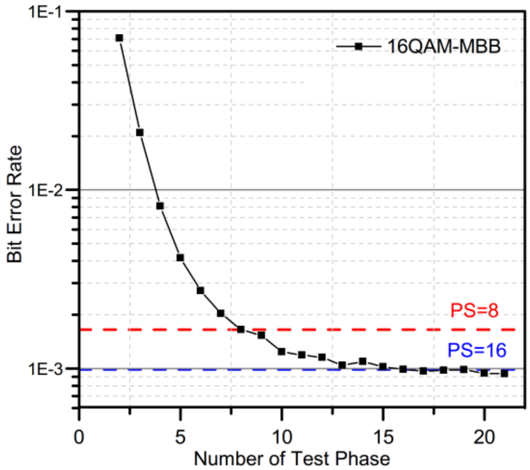

Fig. 2. Simulation results: BER versus the number of test phases B under the proposed MBB algorithm. OSNR=13dB. PS is the number of pilot subcarriers under the PA method.

4. Conclusion

In this paper, we propose a novel image processing technology based common phase noise estimation method for coherent optical OFDM system. Simulation result has shown the newly proposed method has a comparable performance as conventional pilot-aided method, but enjoys a much increased spectral efficiency.

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