Comparative Study on Carrier Phase Estimation Methods in Dispersion-Unmanaged Optical Transmission Systems

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Abstract—**The comparative study on three carrier phase estimation (CPE) methods, involving a one-tap normalized least-mean-square algorithm, a block-wise average algorithm, and a Viterbi-Viterbi algorithm has been carried out in the long-haul high-speed dispersion-unmanaged coherent optical transmission systems. The close-form predictions for bit-error-rate behaviors in these CPE methods have been analyzed by considering both the laser phase noise and the equalization enhanced phase noise.**

Keywords—coherent communication; optical fiber transmission; carrier phase estimation, laser phase noise, equalization enhanced phase noise

I. INTRODUCTION

The performance of long-haul high-speed optical fiber communication systems can be significantly degraded by the transmission system impairments, such as chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise (PN) and fiber nonlinearities (FNLs) [1-10]. Coherent optical detection and digital signal processing (DSP) allows the powerful equalization and mitigation of system impairments in electrical domain, and have become one of the most promising techniques for the next-generation optical fiber communication networks to achieve a performance very close to the Shannon capacity limit, with an entire capture of the amplitude and phase of the optical signals [11-19]. To compensate the phase noise from the laser sources, some feed-forward and feed-back carrier phase estimation (CPE) algorithms have been proposed to estimate the phase of optical carriers [20-28]. Among these CPE approaches, the one-tap normalized least-mean-square (NLMS) algorithm, the block-wise average (BWA) algorithm, and the Viterbi-Viterbi (VV) algorithm have been validated for compensating the laser phase noise effectively, and are also regarded as promising DSP algorithms in the real-time high-speed coherent optical fiber transmission systems [26-28].

In the electronic dispersion compensation (EDC) based optical fiber communication systems, an effect of equalization enhanced phase noise (EEPN) is generated due to the interactions between the EDC module and the laser phase noise [29,30]. The performance of optical fiber communication systems will be degraded seriously by EEPN, with the increase of fiber dispersion, laser linewidths, modulation formats, and symbol rates [31-34]. The effects of EEPN have been studied in the single-channel, the wavelength division multiplexing, the orthogonal frequency division multiplexing, the dispersion pre-distorted, and the multi-mode optical transmission systems [35-39]. Meanwhile, some investigations have also been carried out to study the performance of EEPN in the CPE of long-haul high-speed optical transmission systems [40-42]. Considering the impact of EEPN, the traditional analysis of the CPE algorithms is not suitable any longer for the design and the optimization of the long-haul high-speed optical fiber networks. Correspondingly, it will be interesting and useful to investigate the bit-error-rate (BER) performance in the one-tap NLMS, the BWA, and the VV carrier phase estimation algorithms, when the influence of EEPN is taken into account.

In this paper, the theoretical assessments on the CPE in long-haul coherent optical fiber communication systems using the one-tap NLMS, the BWA, and the VV algorithms are presented and discussed. The close-form expressions for the estimated carrier phase in the three algorithms are derived, and the BER performance such as the BER floors, has been predicted analytically. For different phase noise variance (or effective phase noise variance considering EEPN), the performance of the NLMS, the BWA, and the VV CPE methods have been compared.

II. LASER PHASE NOISE AND EQUALIZATION ENHANCED PHASE NOISE

A. Laser Phase Noise

In coherent optical communication systems, the variance of the phase noise from the transmitter (Tx) laser and the local oscillator (LO) laser can be described as follows [1,2],

$$\sigma^2_{Tx\_LO} = 2\pi\left(\Delta f_{Tx} + \Delta f_{LO}\right)\cdot T_S \tag{1}$$

where Δf_{Tx} and Δf_{LO} are the 3-dB linewidths of the Tx laser and the LO laser respectively, and T_S is the symbol period of coherent system. It is found that the laser phase noise variance decreases with the increment of the signal symbol rate $R_S=1/T_S$.

B. Analysis of Equalization Enhanced Phase Noise

Considering the interplay between the EDC module and the LO laser phase noise, the noise variance of the EEPN in the long-haul optical communication systems can be expressed as the follow equation [29,34],

$$\sigma^2_{EEPN\_LO} = \pi\lambda^2 D \cdot L \cdot \Delta f_{LO} / 2cT_S \tag{2}$$

where D is the CD coefficient of fiber, L is the fiber length, and $\lambda=c/f_{Tx}=c/f_{LO}$ is the central wavelength of optical carrier wave, f_{LO} is the central frequency of LO laser, which is equal to the central frequency of the Tx laser f_{Tx} in the homodyne communication systems.

When EEPN is considered in the CPE, the total effective noise variance in optical transmission systems can be described as the following expression [31,34],

$$\begin{aligned}\sigma^2_T &\approx \sigma^2_{EEPN} + \sigma^2_{Tx\_LO} \\ &\approx \pi\lambda^2 D \cdot L \cdot \Delta f_{LO} / 2cT_S + 2\pi T_S\left(\Delta f_{Tx} + \Delta f_{LO}\right)\end{aligned} \tag{3}$$

III. ANALYSIS OF CARRIER PHASE ESTIMATION

A. One-tap NLMS Carrier Phase Estimation

The transfer function of the one-tap NLMS carrier phase estimation in the coherent optical communication systems can be expressed as follows [25,34],

$$y(k) = w_{NLMS}(k)x(k) \tag{4}$$

$$w_{NLMS}(k+1) = w_{NLMS}(k) + \mu e(k)x^*(k) / |x(k)|^2 \tag{5}$$

$$e(k) = d(k) - y(k) \tag{6}$$

where $x(k)$ is the input symbol, k is the symbol index, $y(k)$ is the output symbol, $w_{NLMS}(k)$ is the tap weight of the one-tap NLMS algorithm, $d(k)$ is the desired output symbol after the CPE, $e(k)$ is the estimation error between the output symbol and the desired output symbol, and μ is the step size of the one-tap NLMS algorithm.

It has been verified that the one-tap NLMS CPE behaves similar to the ideal differential CPE, and the BER floor in the one-tap NLMS CPE for the quadrature phase shift keying (QPSK) optical transmission systems can be approximately described as [25,34]:

$$BER^{NLMS\_QPSK}_{floor} \approx \frac{1}{2} erfc\left(\frac{\pi}{4\sqrt{2}\sigma_T}\right) \tag{7}$$

Therefore, the BER floor in the one-tap NLMS carrier phase estimation for the n-level phase shift keying (n-PSK) coherent optical communication systems can be calculated accordingly [25]:

$$BER^{NLMS}_{floor} \approx \frac{1}{\log_2 n} erfc\left(\frac{\pi}{n\sqrt{2}\sigma_T}\right) \tag{8}$$

where σ^2_T is the total phase noise variance in the n-PSK optical transmission systems.

B. Block-wise Average Carrier Phase Estimation

As an n-th power CPE method, the block-wise average algorithm calculates the n-th power of the received symbols to remove the information of the modulated phase in the n-PSK coherent transmission systems, and the computed phase (n-th power) are summed and averaged over a certain block (the length of the block is called block size). The averaged phase value is then divided over n, and the final result is regarded as the estimated phase for the received symbols within the entire block. For n-PSK coherent optical systems, the estimated carrier phase for each process block using the BWA algorithm can be expressed as [25,27],

$$\phi_{BWA}(k) = \frac{1}{n}\arg\left\{\sum_{p=1+(q-1)\cdot N_{BWA}}^{q\cdot N_{BWA}} x^n(p)\right\} \tag{9}$$

$$q = \lceil k/N_{BWA} \rceil \tag{10}$$

where k is the symbol index, N_{BWA} is the block size of BWA algorithm, and $\lceil x \rceil$ means the closest integer lager than x.

The BER floor in the BWA carrier phase estimation in the n-PSK coherent communication systems can be derived using the Taylor series expansion as [25]:

$$BER^{BWA}_{floor} \approx \frac{1}{N_{BWA}\log_2 n} \cdot \sum_{p=1}^{N_{BWA}} erfc\left(\frac{\pi}{n\sqrt{2}\sigma_{BWA}(p)}\right) \tag{11}$$

$$\sigma^2_{BWA}(p) = \frac{\sigma^2_T}{6N^2_{BWA}}\begin{bmatrix} 2(p-1)^3 + 3(p-1)^2 + 2(N_{BWA}-p)^3 \\ +3(N_{BWA}-p)^2 + N_{BWA} - 1 \end{bmatrix} \tag{12}$$

where σ^2_T is the total phase noise variance in the n-PSK optical transmission systems.

C. Viterbi-Viterbi Carrier Phase Estimation

As another n-th power CPE approach, the Viterbi-Viterbi algorithm also calculates the n-th power of the received symbols to remove the information of the modulated phase. The computed phase are also summed and averaged over the processing block (with a certain block length). Compared to the BWA algorithm, the VV algorithm only treats the extracted phase as the estimated phase for the central symbol in each processing block. The estimated carrier phase in the VV algorithm in the n-PSK coherent transmission systems can be described using the following equation [25,28],

$$\phi_{VV}(k)=\frac{1}{n}\arg\left\{\sum_{q=-(N_{VV}-1)/2}^{(N_{VV}-1)/2} x^{n}(k+q)\right\} \tag{13}$$

where N_{VV} is the block size in the VV algorithm, and is an odd value of e.g. 1,3,5,7…

Using the Taylor expansion, the BER floor in the VV carrier phase estimation for n-PSK coherent communication systems can be assessed and expressed approximately using the following equation [25],

$$BER_{floor}^{VV}\approx\frac{1}{\log_2 n}erfc\left(\frac{\pi}{n\sigma_T}\sqrt{\frac{6N_{VV}}{N_{VV}^2-1}}\right) \tag{14}$$

where σ_T^2 is the variance of the total phase noise in n-PSK optical fiber transmission systems.

IV. RESULTS AND DISUCSSIONS

As shown in Fig. 1, Fig. 2 and Fig. 3, the BER floors versus different phase noise variances (or effective phase noise variance considering EEPN) in the above three carrier phase estimation (the one-tap NLMS, the BWA, and the VV) algorithms in the long-haul high-speed optical fiber communication systems have been comparatively investigated, where the modulation formats of the QPSK (Fig. 1), the 8-PSK (Fig. 2), and the 16-PSK (Fig. 3) have been applied respectively. In these analytical models, the attenuation, the PMD, the fiber nonlinearities are all neglected. A block size of 11 is used in both the block-wise average and the Viterbi-Viterbi carrier phase estimation methods, since the additive noise in the transmission channels such as the amplified spontaneous emission (ASE) noise should also be taken into consideration in practical optical communication systems. The BER floors in the three CPE approaches are evaluated and discussed comparatively in the range from 10^{-6} to 0.5.

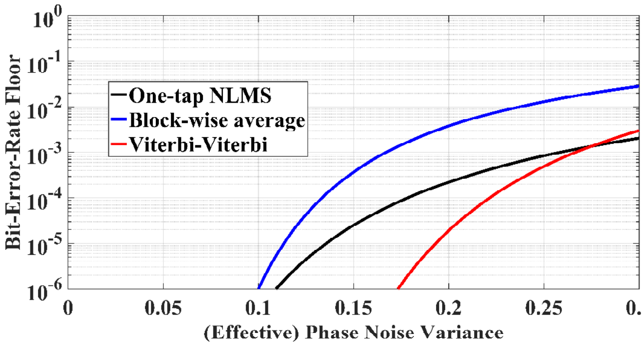

Fig. 1. BER floors versus different phase noise variances in the three carrier phase estimation algorithms in the QPSK optical fiber communication systems. Block sizes of the BWA and the VV algorithms are both 11.

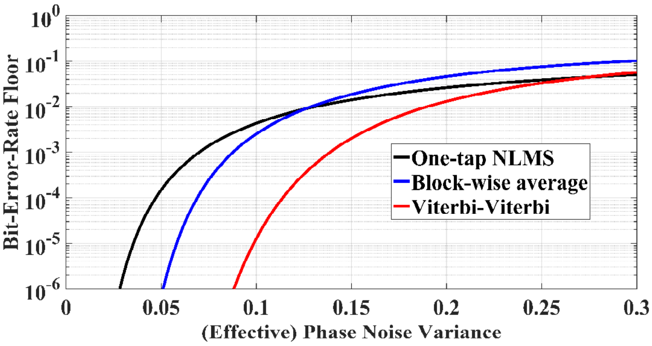

Fig. 2. BER floors versus different phase noise variances in the three carrier phase estimation algorithms in the 8-PSK optical fiber communication systems. Block sizes of the BWA and the VV algorithms are both 11.

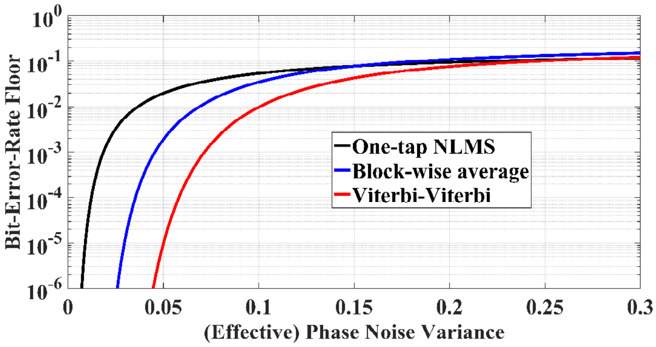

Fig. 3. BER floors versus different phase noise variances in the three carrier phase estimation algorithms in the 16-PSK optical fiber communication systems. Block sizes of the BWA and the VV algorithms are both 11.

It can be found in Fig. 1 that, in the QPSK transmission system, the Viterbi-Viterbi CPE algorithm outperforms the one-tap NLMS and the block-wise average algorithms for small phase noise variance (or effective phase noise variance), while the three CPE algorithms will converge to a similar behavior for the large phase noise variance (or effective phase noise variance). The same trends can be found in the 8-PSK coherent optical transmission system in Fig. 2 and in the 16-PSK coherent optical transmission system in Fig. 3. Meanwhile, it is also found that the difference between the three carrier phase estimation methods becomes smaller for higher-level modulation formats.

V. CONCLUSION

The analytical evaluation of the carrier phase estimation in the long-haul high-speed coherent optical fiber communication systems, using the one-tap normalized least-mean-square algorithm, the block-wise average algorithm, and the Viterbi-Viterbi algorithm, has been investigated, both considering the laser phase noise and the equalization enhanced phase noise. The close-form expressions for estimated carrier phase in the one-tap normalized least-mean-square, the block-wise average, and the Viterbi-Viterbi algorithms have been presented, and the BER performance such as the BER floors, in the three carrier phase estimation methods has been investigated comparatively.

The Viterbi-Viterbi CPE algorithm outperforms the one-tap NLMS and the block-wise average algorithms for small phase noise variance (or effective phase noise variance), while the three CPE algorithms will converge to a similar behavior for the large phase noise variance (or effective phase noise variance). Meanwhile, the difference between the three CPE methods becomes smaller for higher-level modulation formats.

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