Optics Communications 293 (2013) 54–60

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Carrier phase estimation methods in coherent transmission systems influenced by equalization enhanced phase noise

Tianhua Xu [a,b,c,*], Gunnar Jacobsen [b], Sergei Popov [a], Jie Li [b], Ari T. Friberg [a], Yimo Zhang [c]

[a] Royal Institute of Technology, Stockholm SE-16440, Sweden
[b] Acreo AB, Electrum 236, SE-16440 Kista, Sweden
[c] Tianjin University, Tianjin 300072, PR China

ARTICLE INFO

Article history:
Received 9 March 2012
Received in revised form
22 November 2012
Accepted 23 November 2012
Available online 21 December 2012

Keywords:
Coherent optical transmission system
Carrier phase estimation
Equalization enhanced phase noise
Phase shift keying

ABSTRACT

We present a comparative study on three carrier phase estimation algorithms, including a one-tap normalized least mean square (NLMS) method, a block-average method, and a Viterbi–Viterbi method in the *n*-level phase shift keying coherent transmission systems considering the equalization enhanced phase noise (EEPN). In these carrier phase estimation methods, the theoretical bit-error-rate floors based on traditional leading-order Taylor expansion are compared to the practical simulation results, and the tolerable total effective linewidths (involving the transmitter, the local oscillator lasers and the EEPN) for a fixed bit-error-rate floor are evaluated with different block sizes, when the fiber nonlinearities are neglected. The complexity of the three carrier phase estimation methods is also discussed. We find that the carrier phase estimation methods in practical systems should be analyzed based on the simulation results rather than the traditional theoretical predictions, when large EEPN is involved. The one-tap NLMS method can always show an acceptable behavior, while the step size is complicated to optimize. The block-average method is efficient to implement, but it behaves unsatisfactorily when using a large block size. The Viterbi–Viterbi method can show a small improvement compared to the block-average method, while it requires more computational complexity.

1. Introduction

Optical impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), phase noise (PN) and nonlinear effects degrade the performance of high-speed optical fiber transmission systems severely [1–4]. Coherent optical receivers allow the significant equalization of transmission system impairments in the electrical domain, where the fiber dispersion and carrier phase noise can be well compensated by the efficient digital signal processing (DSP) [5–8]. Several feed-forward and feed-back carrier phase estimation (CPE) algorithms have been validated as the effective methods for mitigating the phase fluctuation from the laser sources [9–13]. However, in these algorithms, the analysis of the phase noise in the transmitter (TX) and the local oscillator (LO) lasers is often lumped together, and the interaction between the large chromatic dispersion and the laser phase noise is neglected.

The complicated interplay between the electronic CD equalization and the laser phase noise has been investigated in recent work, and this leads to an effect of equalization enhanced phase noise (EEPN) [14–24]. Shieh, Ho and Lau et al. have provided the theoretical evaluation for the EEPN based on the enhancement of the LO phase noise due to the dispersion equalization, and they also analyzed the EEPN induced time jitter in coherent systems [14–17]. Xie has investigated the influence of large CD on the LO phase noise to amplitude noise conversion, and the impact of large CD on the fiber nonlinear effects [18,19]. Fatadin and Savory have studied the impacts of the EEPN in quadrature phase shift keying (QPSK), 16-level quadrature amplitude modulation (16-QAM) and 64-QAM transmission systems [20]. Meanwhile, the effects of EEPN have also been investigated in the orthogonal frequency division multiplexing (OFDM) transmission systems [22]. In our previous work, we have carried out a detailed analysis of the one-tap normalized least mean square (NLMS) carrier phase estimation method in the coherent system considering the impact of EEPN [23]. We have also proved that it is difficult to compensate the EEPN entirely, even using an optical reference carrier [24]. The EEPN scales with the increment of the fiber length, the symbol rate, and the LO laser linewidth [14–16], and it will significantly degrade the performance of the coherent optical communication systems. Involving the impact of EEPN, the traditional analysis for carrier phase estimation in coherent systems, where only pure laser phase noise are taken into account, may not be suitable again. Therefore, it is important to investigate in detail the performance of different

* Corresponding author at: Optics Group, KTH-Electrum 229, Kista, Stockholm SE-16440, Sweden. Tel.: +46 762178043; fax: +46 87896672.
E-mail addresses: tianhua@kth.se, xutianhua0629@yahoo.com.cn (T. Xu).

0030-4018/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.optcom.2012.11.090

carrier phase extraction methods in the coherent optical communication systems considering the EEPN.

In this paper, we present a comparative analysis on the performance of different carrier phase estimation methods in the coherent optical transmission system considering the equalization enhanced phase noise. Three carrier phase extraction algorithms, including a one-tap normalized least mean square method, a block-average (BA) method, and a Viterbi–Viterbi (VV) method are investigated for the phase noise mitigation in the n-level phase shift keying (n-PSK) coherent communication systems [10–13]. For the first time to our knowledge, the influence of EEPN is analyzed by using and comparing the analytical approximations and the simulation results of the three CPE methods. The numerical simulations are carried out in a 112-Gbit/s non-return-to-zero polarization division multiplexed quadrature phase shift keying (NRZ-PDM-QPSK) coherent transmission system, which is implemented in the VPI simulation platform [25]. The theoretical bit-error-rate (BER) floors in the three CPE methods including the impact of EEPN are calculated based on the leading order of the Taylor expansion, which is the commonly used approach in the BER floor prediction for the CPE algorithms [26–28]. The theoretical predictions are compared to the practical simulation results. Meanwhile, the tolerable total effective linewidths (involving the TX, the LO lasers and the EEPN) in the three CPE methods with different block sizes are evaluated for a fixed BER floor, where the influence of the fiber nonlinearities are neglected. The computational complexity of the three carrier phase extraction methods is also discussed. Our analysis and discussions are useful and important for the practical design and application of the carrier phase estimation algorithms in long-haul high speed coherent optical transmission systems, where a large EEPN should be considered.

2. Analysis for total phase noise variance considering EEPN

In the coherent communication system with electronic CD equalization, the transmitter phase noise passes through both transmission fibers and the digital CD equalization module, and so the net dispersion experienced by the transmitter PN is close to zero. However, the local oscillator phase noise only goes through the electronic CD equalization module, and will be significantly enhanced due to the digital dispersion equalization [14–18].

The EEPN scales linearly with the accumulated chromatic dispersion and the linewidth of the LO laser, and the variance of the additional noise due to the EEPN can be expressed as follows, see e.g. [14,15]

$$\sigma_{EEPN}^2 = \frac{\pi\lambda^2}{2c}\cdot\frac{D\cdot L\cdot\Delta f_{LO}}{T_S} \tag{1}$$

where λ is the central wavelength of the optical carrier wave, c is the light speed in vacuum, D is the CD coefficient of the transmission fiber, L is the fiber length, Δf_{LO} is the 3-dB linewidth of the LO laser, and T_S is the symbol period of the transmission system.

Therefore, the total phase noise variance in the coherent transmission system including the EEPN can be expressed as

$$\sigma^2 = \sigma_{TX}^2+\sigma_{LO}^2+\sigma_{EEPN}^2+2\rho\cdot\sigma_{LO}\sigma_{EEPN} \approx \sigma_{TX}^2+\sigma_{LO}^2+\sigma_{EEPN}^2 \tag{2}$$

$$\sigma_{TX}^2 = 2\pi\Delta f_{TX}\cdot T_S \tag{3}$$

$$\sigma_{LO}^2 = 2\pi\Delta f_{LO}\cdot T_S \tag{4}$$

where σ^2 represents the total phase noise variance, σ_{TX}^2 and σ_{LO}^2 are the intrinsic phase noise variance of the TX and the LO lasers, respectively, Δf_{TX} is the 3-dB linewidth of the TX laser, and ρ is the correlation coefficient between the EEPN and the intrinsic LO phase noise. We note that the approximation in Eq. (2) is valid when the transmission length for the normal single mode fiber exceeds the order of 80 km [23].

Corresponding to the definition of the intrinsic phase noise from TX and LO lasers, we employ an effective linewidth Δf_{Eff} to describe the total phase noise in the coherent system with EEPN [23,24], which can be defined as the following expression:

$$\Delta f_{Eff} = \frac{\sigma_{TX}^2+\sigma_{LO}^2+\sigma_{EEPN}^2+2\rho\cdot\sigma_{LO}\sigma_{EEPN}}{2\pi T_S} \approx \frac{\sigma_{TX}^2+\sigma_{LO}^2+\sigma_{EEPN}^2}{2\pi T_S} \tag{5}$$

3. Principle of carrier phase estimation with EEPN

3.1. Principle of normalized LMS phase estimation

The one-tap NLMS filter can be employed effectively for carrier phase estimation [10], of which the tap weight is expressed as

$$w(p+1) = w(p)+\frac{\mu}{|x(p)|^2}x^*(p)e(p) \tag{6}$$

$$e(p) = d(p)-w(p)\cdot x(p) \tag{7}$$

where $w(p)$ is the complex tap weight, $x(p)$ is the complex magnitude of the input signal, p represents the number of the symbol sequence, $d(p)$ is the desired symbol, $e(p)$ is the estimation error between the output signals and the desired symbols, and μ is the step size parameter.

The phase estimation using the one-tap NLMS filter resembles the performance of the ideal differential detection [23], and the BER floor for the n-PSK transmission systems using the one-tap NLMS carrier phase estimation can be approximately described by the following expression:

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

where σ is the square root of the total phase noise variance.

3.2. Principle of block-average phase estimation

The block-average method computes the nth power of the symbols in each process unit to cancel the phase modulation, and the calculated phase is summed and averaged over the entire block (the length of the entire block is called block size). Then the phase is divided by n, and the result leads to a phase estimate for the entire block [11]. For the n-PSK transmission system, the estimated carrier phase for each process unit using the BA method can be expressed as

$$\hat{\Phi}_{BA}(p) = \frac{1}{n}\arg\left\{\sum_{k=1+(m-1)\cdot N_b}^{m\cdot N_b} x^n(k)\right\} \tag{9}$$

$$m = \left\lceil\frac{p}{N_b}\right\rceil \tag{10}$$

where N_b is the block size in the BA method, and $\lceil x\rceil$ represents the nearest integer larger than x.

Using a Taylor series expansion, the BER floor in the block-average carrier phase estimation for the n-PSK transmission system can be approximately expressed as follows—see e.g. [26,27]

$$BER_{floor}^{BA} \approx \frac{1}{N_b\log_2 n}\cdot\sum_{k=1}^{N_b} erfc\left(\frac{\pi}{n\sqrt{2}\sigma_{BA,k}}\right) \tag{11}$$