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Analytical BER performance in differential *n*-PSK coherent transmission system influenced by equalization enhanced phase noise

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ABSTRACT

Long-haul high speed optical transmission systems are significantly distorted by the interplay between the electronic chromatic dispersion (CD) equalization and the local oscillator (LO) laser phase noise, which leads to an effect of equalization enhanced phase noise (EEPN). The EEPN degrades the performance of optical communication systems severely with the increment of fiber dispersion, LO laser linewidth, symbol rate, and modulation format. In this paper, we present an analytical model for evaluating the performance of bit-error-rate (BER) versus signal-to-noise ratio (SNR) in the *n*-level phase shift keying (*n*-PSK) coherent transmission system employing differential carrier phase estimation (CPE), where the influence of EEPN is considered. Theoretical results based on this model have been investigated for the differential quadrature phase shift keying (DQPSK), the differential 8-PSK (D8PSK), and the differential 16-PSK (D16PSK) coherent transmission systems. The influence of EEPN on the BER performance in term of the fiber dispersion, the LO phase noise, the symbol rate, and the modulation format are analyzed in detail. The BER behaviors based on this analytical model achieve a good agreement with previously reported BER floors influenced by EEPN. Further simulations have also been carried out in the differential CPE considering EEPN. The results indicate that this analytical model can give an accurate prediction for the DQPSK system, and a leading-order approximation for the D8PSK and the D16PSK systems.

1. Introduction

Coherent optical detection allows the significant equalization of transmission system impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), phase noise (PN), and fiber nonlinearities (FNLs) in the electrical domain by using the powerful digital signal processing (DSP) [1–7]. The carrier phase estimation (CPE) can be effectively implemented by employing the feedforward and the feedback algorithms [7–11]. As a conventional feedforward algorithm, the differential phase estimation has been validated as a simple and effective method for the phase noise compensation (PNC) in the coherent transmission system, which is also regarded as a benchmark for evaluating the CPE approaches [12–17]. However, the analysis of the phase noise in the transmitter (Tx) and the local oscillator (LO) lasers is often lumped together, and the interplay between the CD and the PN is not considered in the traditional evaluation of carrier phase estimation (including differential phase estimation). Shieh et al. have provided the theoretical assessment to evaluate the equalization enhanced phase noise (EEPN) from the interaction between the LO phase fluctuation and the fiber dispersion [18–21]. Xie has investigated the impacts of CD on both the LO phase noise to amplitude noise conversion and the fiber nonlinear effects [22,23]. Fatadin et al. have also studied the influence of the EEPN in quadrature phase shift keying (QPSK), 16-level quadrature amplitude modulation (16-QAM) and 64-QAM coherent transmission systems [24]. Meanwhile, the influence of EEPN on different CPE algorithms has also been investigated in detail by using numerical simulations [25–29]. Due to the EEPN, the requirement of laser linewidth cannot be generally relaxed for the transmission system with a higher symbol rate. It would be of importance to investigate the analytical estimation for the performance of bit-error-rate (BER) versus signal-to-noise ratio (SNR) in the

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carrier phase estimation in coherent optical transmission system considering the influence of EEPN.

In this paper, we present an analytical model for assessing the behavior of BER versus SNR in the differential phase estimation in the long-haul high speed n-level phase shift keying (n-PSK) coherent optical transmission system, where the impact of EEPN is considered. The additional noise variance induced by EEPN has been taken into account in the analytical estimation. Based on this model, we have investigated the performance of BER versus SNR in the differential QPSK (DQPSK), the differential 8-PSK (D8PSK), and the differential 16-PSK (D16PSK) coherent optical transmission systems in detail involving the influence of EEPN. Theoretical results demonstrate that the behaviors of BER versus SNR in the differential phase estimation are significantly distorted by EEPN, with the increment of the LO phase noise, the accumulated fiber dispersion, the symbol rate, and the modulation format. Meanwhile, the results from this model make a good agreement with our previously reported BER floors. Moreover, to investigate the accuracy of this analytical model, numerical simulations have also been implemented for the DQPSK, the D8PSK, and the D16PSK coherent transmission systems with differential carrier phase estimation, considering EEPN. The results indicate that this analytical model can give an accurate prediction for the DQPSK system, and a leading-order approximation for the D8PSK and the D16PSK systems, when EEPN is considered.

2. Differential carrier phase estimation in coherent transmission system

The setup of n-PSK coherent optical transmission system is illustrated in Fig. 1, where the differential carrier phase estimation is employed. The pseudorandom bit sequence (PRBS) data are differentially encoded and modulated into the n-PSK optical signals, and then fed into the transmission fiber channel. In the receiver end, the received optical signals are mixed with the LO laser and converted into the electrical signals by the photodiodes (PDs). Then the electrical signals are sampled by the analog-to-digital convertors (ADCs) at twice the symbol rate. The digitalized signals are processed by the DSP algorithms, including CD compensation, signal equalization, and differential carrier phase estimation, to mitigate the system impairments.

The differential carrier phase estimation is applied for the carrier phase recovery in the coherent optical detection, where the information is encoded in and extracted from the phase difference between two consecutive symbols [12–17]. In the differential CPE, the k-th symbol information is recovered from the phase difference between the current k-th symbol and the $(k+1)$-th symbol. Hence, the phase ambiguity $\Delta\varphi$ in the recovered data comes from the carrier phase fluctuation between the two adjacent symbols $\Delta\varphi=\varphi_k-\varphi_{(k+1)}$, during a symbol period [12–17]. Compared to other CPE algorithms such as the block-average (BA) and the Viterbi–Viterbi (VV) methods [7,9,14], differential phase estimation does not require any computational operations of n-power, averaging, and phase unwrapping, and can thus be efficiently implemented in the field-programmable gate array (FPGA) hardware [17]. In the following sections, we will investigate the BER performance in the differential carrier phase estimation considering the impact of EEPN, and our study can be employed as the benchmark and reference for evaluating the effects of EEPN in other CPE methods.

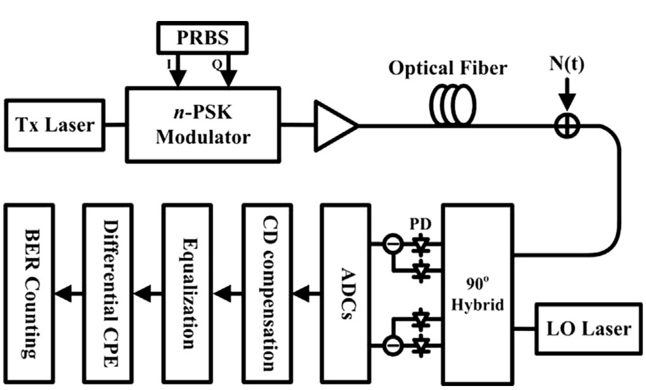

Fig. 1. Schematic of coherent optical transmission system with differential carrier phase estimation. N(t): additive white Gaussian noise (AWGN).

3. Principle of equalization enhanced phase noise

The schematic of EEPN in the coherent optical communication system employing electronic CD post-equalization and carrier phase estimation is depicted in Fig. 2. The Tx laser phase noise passes through both the transmission fiber and the digital CD equalization module, and therefore the net dispersion experienced by the transmitter PN is close to zero. However, the LO phase noise only goes through the digital CD equalization module, of which the transfer function is heavily dispersed in the transmission system without using any optical dispersion compensation (ODC). Consequently, the LO phase noise will interact with the CD equalization module, and will significantly influence the performance of the long-haul high speed coherent system.

It has been demonstrated that the EEPN scales linearly with the accumulated CD, the linewidth of LO laser, and the symbol rate [18–20], and the variance of the additional noise due to the EEPN can be expressed as

$$\sigma^2_{EEPN}=\frac{\pi\lambda^2}{2c}\frac{DL\Delta f_{LO}}{T_S} \tag{1}$$

where λ is the central wavelength of the optical wave, c is the light speed in vacuum, D is the CD coefficient of 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 coherent transmission system.

4. BER performance in differential CPE considering EEPN

The theoretical performance of BER versus SNR in the n-PSK coherent optical transmission system employing differential carrier phase estimation can be calculated according to the following

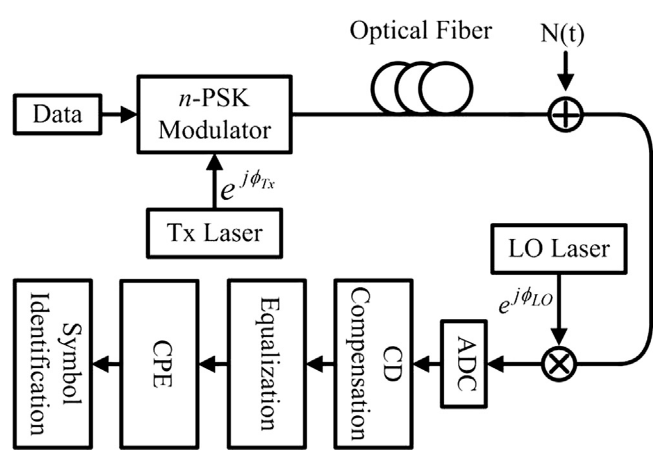

Fig. 2. Schematic of EEPN in the coherent transmission system. N(t): additive white Gaussian noise (AWGN), ADC: analog-to-digital convertor.