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Analysis of chromatic dispersion compensation and carrier phase recovery in long-haul optical transmission system influenced by equalization enhanced phase noise

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ABSTRACT

The performance of long-haul coherent optical fiber transmission system is significantly affected by the equalization enhanced phase noise (EEPN), due to the interaction between the electronic dispersion compensation (EDC) and the laser phase noise. In this paper, we present a comprehensive study on different chromatic dispersion (CD) compensation and carrier phase recovery (CPR) approaches, in the n-level phase shift keying (n-PSK) and the n-level quadrature amplitude modulation (n-QAM) coherent optical transmission systems, considering the impacts of EEPN. Four CD compensation methods are considered: the time-domain equalization (TDE), the frequency-domain equalization (FDE), the least mean square (LMS) adaptive equalization are applied for EDC, and the dispersion compensating fiber (DCF) is employed for optical dispersion compensation (ODC). Meanwhile, three carrier phase recovery methods are also involved: a one-tap normalized least mean square (NLMS) algorithm, a block-wise average (BWA) algorithm, and a Viterbi-Viterbi (VV) algorithm. Numerical simulations have been carried out in a 28-Gbaud dual-polarization quadrature phase shift keying (DP-QPSK) coherent transmission system, and the results indicate that the origin of EEPN depends on the choice of chromatic dispersion compensation methods, and the effects of EEPN also behave moderately different in accordance to different carrier phase recovery scenarios.

1. Introduction

Long-haul high speed optical fiber communications pose strict requirements of their tolerance to the linear and the nonlinear channel distortions [1–3]. Coherent optical transmission employing digital signal processing (DSP) allows the compensation of system impairments, such as chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase

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noise (PN), and fiber nonlinearities (FNLs), in the electrical domain [4–12]. Using powerful DSP algorithms, the equalization of fiber chromatic dispersion and the compensation of laser phase noise have been carried out effectively in coherent transmission systems according to the reported work [3–10]. The electronic dispersion compensation (EDC) can be implemented by using the digital filters in both the time domain and the frequency domain [4–6,13–16], and the carrier phase recovery (CPR) can be realized by using the feed-forward and the feed-back DSP algorithms [8–10,17–19]. However, in these conventional EDC and CPR algorithms, the analysis of the phase noise from the transmitter (Tx) and the local oscillator (LO) lasers was always lumped together, where the interplay between the dispersion compensating module (DCM) and the laser phase noise was not considered.

Recently, the interaction between the electronic dispersion equalization and the laser phase noise, which leads to an effect of equalization enhanced phase noise (EEPN), has attracted the research interests due to its significant impacts in long-haul optical transmission systems [20–35]. W. Shieh et al. have reported the theoretical assessment of the EEPN from the enhanced LO phase noise, and they also investigated the EEPN induced time jitter in coherent transmission systems [20–23]. C. Xie has studied the effects of EDC on both the LO phase noise to amplitude noise conversion and the fiber nonlinear interference [24,25]. I. Fatadin et al. have investigated the influence of EEPN in the n-level quadrature amplitude modulation (n-QAM) systems, such as the quadrature phase shift keying (QPSK), the 16-QAM and the 64-QAM coherent optical communication systems [26]. The impacts of EEPN have also been investigated in the optical orthogonal frequency division multiplexing (OFDM) transmission systems [28,29]. Meanwhile, some experimental studies regarding EEPN have also been carried out in the QPSK transmission systems [30,31]. In addition, some approaches have also been investigated to mitigate the EEPN, by using the traditional CPR algorithms [32,33], the differential phase estimation [34], the pre-compensation of chromatic dispersion [35], the digital coherence enhancement [27], the optical reference carrier [36,37], and the partially modulated optical carrier [38,39]. Among these methods, the digital coherence enhancement can offer an effective compensation of EEPN [27], while it requires a complicated hardware implementation to measure the LO laser phase fluctuation. The impact of EEPN scales with the increment of fiber length, laser linewidth, symbol rate and modulation format, and significantly degrades the performance of the long-haul high speed coherent optical communication systems [20–34]. The conventional analysis of CD compensation and carrier phase recovery, which only takes into account the intrinsic Tx and LO lasers phase noise, is not suitable any longer for the long-haul coherent transmission system with a considerable EEPN. Therefore, it is of importance to investigate in detail the performance of different chromatic dispersion compensation and carrier phase recovery approaches in the long-haul coherent optical communication systems, where the influence of EEPN is not negligible.

In this paper, built on our previous work where the performance of carrier phase recovery was studied in the transmission system using frequency-domain dispersion compensation [32], we present a comprehensive investigation on different chromatic dispersion compensation and carrier phase recovery methods in the n-level phase shift keying (n-PSK) and n-QAM coherent optical transmission systems considering the impacts of equalization enhanced phase noise. Four chromatic dispersion compensation methods are considered, including the time-domain equalization (TDE), the frequency-domain equalization (FDE), the least mean square (LMS) adaptive equalization for EDC, and the dispersion compensating fiber (DCF) for optical dispersion compensation (ODC). Three carrier phase recovery methods are applied for the laser phase noise compensation: a one-tap normalized least mean square (NLMS) algorithm, a block-wise average (BWA) algorithm, and a Viterbi-Viterbi (VV) algorithm. The origin and the impact of EEPN are analyzed and discussed in detail by using and comparing different chromatic dispersion compensation and carrier phase recovery approaches. Numerical simulations have been implemented in a 28-Gbaud non-return-to-zero dual-polarization QPSK (NRZ-DP-QPSK) coherent optical transmission system, based on the Virtual Photonics Instruments (VPI) and the Matlab software [40,41]. Simulation results indicate that the origin of EEPN depends on the choice of chromatic dispersion compensation methods, and the effects of EEPN behave moderately different in diverse carrier phase recovery approaches. In the transmission system using EDC, the performance of the system employing the TDE and the FDE dispersion equalization is significantly affected by the equalization enhanced LO phase noise (EELOPN). However, in the LMS adaptive dispersion equalization, the system performance is equally influenced by the equalization enhanced Tx phase noise (EETxPN) and the equalization enhanced LO phase noise. There is no EEPN in the transmission system using optical dispersion compensation. In the study of CPR approaches for mitigating EEPN, the one-tap NLMS algorithm gives a marginally worse (but still acceptable) performance than the block-wise average and the Viterbi-Viterbi approaches, when all the CPR methods are applied with an optimum operation. Meanwhile, the Viterbi-Viterbi algorithm only performs slightly better than the block-wise average algorithm, even though it requires more computational complexity. Our analysis and discussions are helpful and important for the practical design and application of the chromatic dispersion compensation and the carrier phase recovery in long-haul high speed coherent optical fiber transmission systems, where the EEPN cannot be neglected.

2. Equalization enhanced phase noise in coherent transmission system

The schematic of coherent optical fiber transmission system employing electronic CD equalization and carrier phase recovery is illustrated in Fig. 1. As an example, we consider the use of a fixed TDE or FDE for the CD equalization [4,15,17,20]. In such cases, the phase noise from Tx laser passes through both the optical fiber and the EDC module, and the net experienced dispersion is close to zero. By contrast, the phase noise from LO laser only goes through the EDC module, which is heavily dispersed in the transmission system without using any optical dispersion compensation. Therefore, the LO phase noise will interplay with the EDC module, and the induced EEPN will significantly affect the performance of the long-haul high speed