Phase noise mitigation in coherent transmission system using a pilot carrier

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ABSTRACT

In this paper, we investigate the phase noise elimination employing an optical pilot carrier in the high speed coherent transmission system considering the equalization enhanced phase noise (EEPN). The numerical simulations are performed in a 28-Gsymbol/s quadrature phase shift keying (QPSK) coherent system with a polarization multiplexed pilot carrier. The carrier phase estimation is implemented by the one-tap normalized least mean square (NLMS) filter and the differential phase detection, respectively. Simulation results demonstrate that the application of the optical pilot carrier is very effective for the intrinsic laser phase noise cancellation, while is less efficient for the EEPN mitigation.

Key Words: Coherent transmission system, quadrature phase shift keying, phase noise mitigation, chromatic dispersion, equalization enhanced phase noise, pilot carrier

1. INTRODUCTION

Coherent detection allows significant equalization of system impairments such as chromatic dispersion (CD) and phase noise (PN) in the electrical domain[1-3], and has become one of the most promising techniques for the next generation communication networks. The cancellation of the phase noise using a pilot carrier (PC) has been validated as an effective method in coherent transmission system[4,5]. However, in these reported results only the performance of short distance transmission systems is investigated, where the influence of the large CD on the phase noise can be neglected[4,5]. Recent studies have demonstrated that the equalization enhanced phase noise (EEPN) takes the dominant role in the carrier phase estimation (CPE) for the long-haul coherent transmission system due to the interplay between the digital CD equalization and the laser phase noise[6-8]. Thus, it is important to investigate the phase noise mitigation employing the pilot carrier in the long-haul coherent optical communication system considering the EEPN.

In this paper, we employ a polarization multiplexed optical pilot carrier to eliminate the phase noise in the long-haul coherent transmission system considering the EEPN. The performance of the phase noise mitigation using the pilot carrier is investigated in a 28-Gsymbol/s non-return-to-zero quadrature phase shift keying (NRZ-QPSK) coherent transmission system. The carrier phase estimation is implemented by the one-tap normalized least mean square (NLMS) filter and the differential phase detection, respectively[9,10]. Numerical results demonstrate that the application of the optical pilot carrier is very effective for eliminating the intrinsic laser phase noise, while is less efficient for mitigating the significant EEPN.

2. PRINCIPLE OF EQUALIZATION ENHANCED PHASE NOISE

The scheme of the coherent optical communication system with digital CD equalization and carrier phase estimation is depicted in Fig. 1. The transmitter laser signal including the 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 digital CD equalization module, which is heavily dispersed in a transmission system without dispersion compensation fibers (DCFs). Therefore, the LO phase noise will significantly influence the performance of the high speed coherent system with only digital CD post-compensation. We note that the EEPN does not exist in a transmission system with entire optical dispersion compensation for instance using DCFs.

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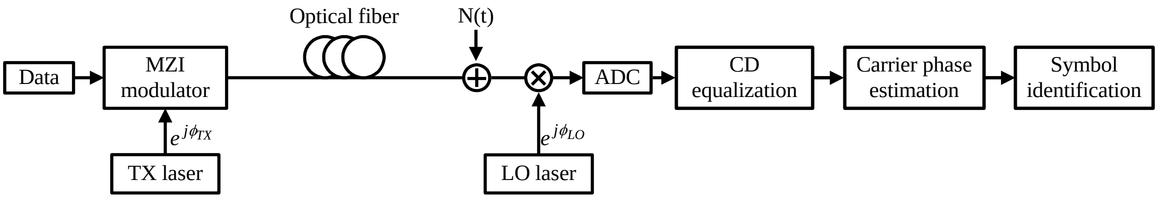


Fig. 1. Scheme of equalization enhanced phase noise in coherent transmission system. MZI: Mach-Zehnder interferometer, Φ_{TX}: phase fluctuation of the TX laser, Φ_{LO}: phase fluctuation of the LO laser, N(t): additive white Gaussian noise, ADC: analog-to-digital convertor.

Theoretical analysis demonstrates that the equalization enhanced phase noise 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[6-8]:

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

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

It is worth noting that the theoretical evaluation of the enhanced LO phase noise is only appropriate for the FD-FIR and the BLU dispersion equalization, which represent the inverse function of the fiber transmission channel without involving the phase noise mitigation. The phase noise from the TX and the LO lasers will be equally enhanced due to the least-mean-square (LMS) adaptive dispersion equalization.

3. ONE-TAP NORMALIZED LMS FILTER FOR PHASE ESTIMATION

3.1 Principle of normalized LMS filter

The one-tap NLMS filter can be employed effectively for carrier phase estimation[9], of which the tap weight is expressed as follows,

$$w_{NLMS}(n+1) = w_{NLMS}(n) + \frac{\mu_{NLMS}}{|x_{PN}(n)|^2} x_{PN}^*(n) e_{NLMS}(n) \tag{2}$$

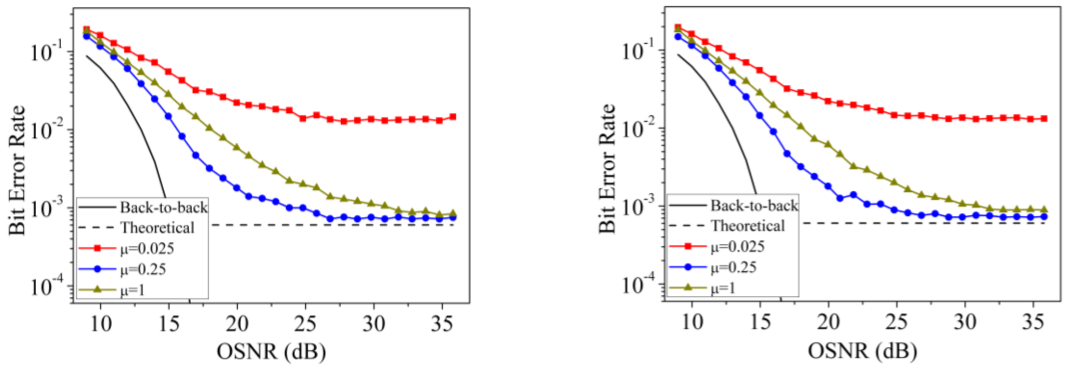
$$e_{NLMS}(n) = d_{PE}(n) - w_{NLMS}(n) \cdot x_{PN}(n) \tag{3}$$

where $w_{NLMS}(n)$ is the complex tap weight, $x_{PN}(n)$ is the complex magnitude of the input signal, n represents the number of the symbol sequence, $d_{PE}(n)$ is the desired symbol, $e_{NLMS}(n)$ is the estimation error between the output signals and the desired symbols, and μ_{NLMS} is the step size parameter.

It has been demonstrated that the one-tap NLMS carrier phase estimation can be implemented by using the feed-forward control scheme[9]. Therefore, it is not difficult to implement the NLMS-CPE in a parallel-processing circuit for the real-time QPSK coherent transmission system.

3.2 Optimization of the step size in NLMS filter

According to the reported investigation, the step size μ_{NLMS} has an optimal value to provide the best performance of the one-tap NLMS phase estimator for a certain laser phase noise[9]. Roughly speaking, a smaller step size will deteriorate the BER floor induced by the laser phase noise due to the fast phase changing occurring in the long effective symbol average-span. By contrast, a larger step size will degrade the NLMS phase estimator on the sensitivity of optical signal-to-noise ratio (OSNR), but influence the BER floor induced by the phase fluctuation little. The performance of the one-tap NLMS-CPE using different step size is shown in Fig. 2, where both of the TX and LO lasers linewidths are 5 MHz, and the fiber length is 2000 km. We can see that the one-tap NLMS-CPE shows the best performance when using the optimum step size (μ=0.25), and the BER floor in NLMS-CPE is deteriorated obviously when the smaller step size (μ=0.025) is used. Meanwhile, we find that only the OSNR sensitivity is degraded while the BER floor has no significant variation, when the larger step size (μ=1) is employed in the one-tap NLMS-CPE. Note that the OSNR value is all defined in 0.1 nm and the penalty between the back-to-back result and the theoretical limit (at BER=10^{-3}) is around 1.8 dB.

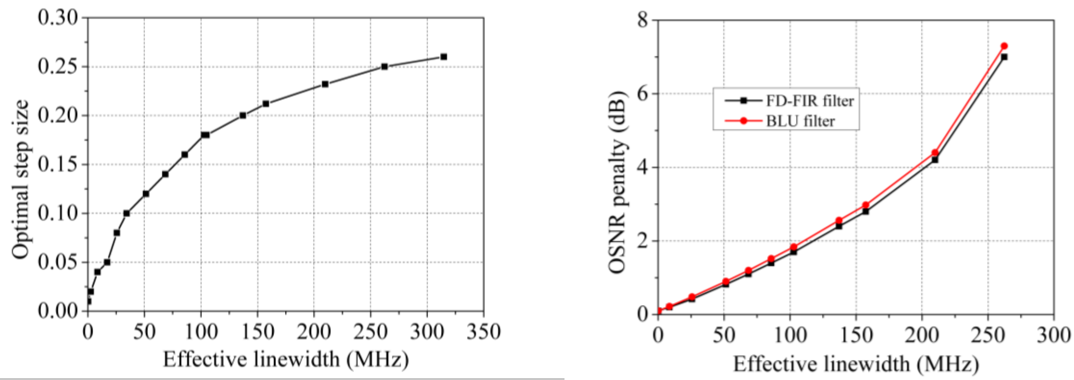


(a) (b)

Fig. 2. Phase estimation using the one-tap NLMS filter with different value of step size, μ is the step size. (a) NLMS-CPE with FD-FIR dispersion equalization, (b) NLMS-CPE with BLU dispersion equalization.

From the above analysis, it is important to determine the optimum step size in the application of the one-tap NLMS phase estimation. Corresponding to the definition of the original 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, which can be defined as the following expression:

$$\Delta f_{Eff} = \frac{\sigma_{TX}^2 + \sigma_{LO}^2 + \sigma_{EEPN}^2}{2\pi T_S} \tag{4}$$



(a) (b)

Fig. 3. The optimum step size and the OSNR penalty in NLMS-CPE. (a) optimum step size for different effective linewidth, (b) OSNR penalty in NLMS phase estimation with the optimum step size for FD-FIR and BLU equalization.

In Fig. 3(a), we studied the optimum step size for different effective linewidth in the 112-Gbit/s NRZ-PDM-QPSK coherent optical transmission system, which is applicable for both the FD-FIR filter and the BLU filter. It is found that the optimum step size increases with the effective laser linewidth. Note that the one-tap NLMS filter is employed with the optimum step size value for phase estimation in our simulation work.

Using the FD-FIR and the BLU dispersion equalization, the OSNR penalty from back-to-back result at BER=10^{-3} in the one-tap NLMS-CPE with the optimum step size are illustrated in Fig. 3(b). It is found that the OSNR penalty scales exponentially with the increment of the effective laser linewidth.

4. SETUP OF NRZ-QPSK TRANSMISSION SYSTEM WITH PILOT CARRIER

As illustrated in Fig. 4, the setup of the 28-Gsymbol/s NRZ-QPSK coherent transmission system with the polarization multiplexed pilot carrier is implemented in the VPI simulation platform[11]. The data output from two the 28-Gbit/s pseudo random bit sequence (PRBS) generators are modulated into the 28-Gsymbol/s NRZ-QPSK optical signal by the Mach-Zehnder modulator. This modulated optical signal utilizes one polarization state of the transmission channel. The orthogonal polarization state is employed to transmit the pilot carrier, which is the reference for laser phase noise cancellation. The two orthogonally polarized optical signals are integrated into one fiber channel by the polarization beam combiner (PBC). In the coherent receiver, the received optical signals are mixed with the local oscillator (LO) laser to be transformed into four electrical signals by the photodiodes, which are then digitalized by the 8-bit analog-to-digital convertors (ADCs) at twice the symbol rate. Afterwards, both the data signals and the pilot carrier are processed by CD equalization module, and the data signals are multiplied by the conjugation of the pilot carrier to eliminate the influence of the laser phase noise.

The central wavelength of the TX and the LO lasers are both 1553.6 nm, and the transmission fiber has the CD coefficient D=16 ps/nm/km. Here we neglect the influences of fiber attenuation, polarization mode dispersion and nonlinear effects. The CD is compensated by the frequency domain equalizer (FDE)[12]. The carrier phase estimation is realized by the one-tap NLMS filter and the differential detection, respectively[9,10].

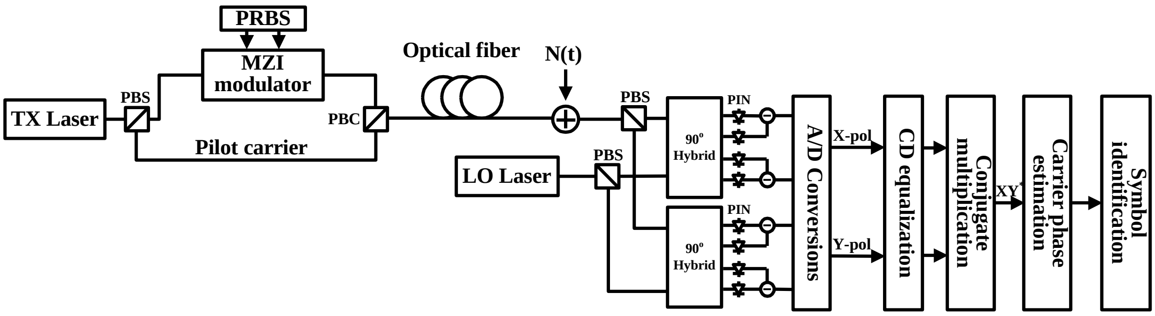


Fig. 4. Schematic of 28-Gsymbol/s NRZ-QPSK coherent transmission system with polarization multiplexed pilot carrier

5. SIMULATION RESULTS

The performance of the phase noise mitigation using the pilot carrier for 2000 km fiber transmission system is illustrated in Fig. 5, where the carrier phase estimation is implemented by the one-tap NLMS filter. In Fig. 5(a), the TX laser linewidth is 170 MHz and the LO laser linewidth is 0 Hz. This means the EEPN is absent in the system. It is found that the laser phase noise can be significantly eliminated by using the optical pilot carrier. In Fig. 5(b), both the TX and the LO lasers linewidth are 5 MHz. This means the EEPN plays the dominant role in the system. We find that the BER performance is improved slightly by using the pilot carrier in this case. This reflects the facts that the EEPN can result in the complex combination of the pure phase noise, the amplitude noise and the time jitter, which are difficult to compensate entirely[6-8].

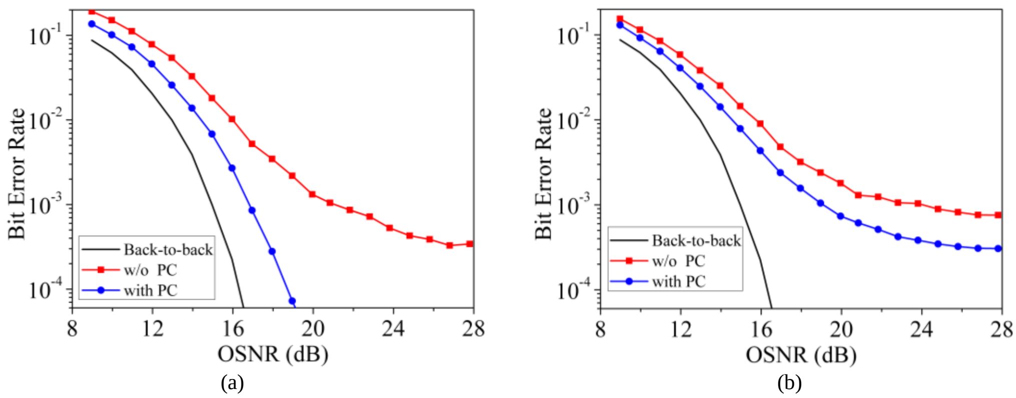


Fig. 5. Carrier phase estimation using NLMS filter for 2000 km fiber transmission, (a) TX linewidth is 170 MHz, LO linewidth is 0Hz, (b) both TX and LO linewidth are 5 MHz. w/o: without.

Figure 6 shows the performance of the phase noise cancellation using the pilot carrier for 2000 km fiber transmission system, where the carrier phase estimation is implemented by the differential phase detection. In Fig 6(a), the TX laser linewidth is 170 MHz and LO laser linewidth is 0 Hz, that also indicates the absence of EEPN. We find that the effective cancellation of the phase noise is achieved by using the pilot carrier. In Fig. 6(b), both the TX and the LO lasers linewidth are 5 MHz, and the EEPN plays the dominant role in the system. We also find that slight improvement of the BER performance is achieved by using the pilot carrier in this case, which is very similar to the one-tap NLMS phase estimation.

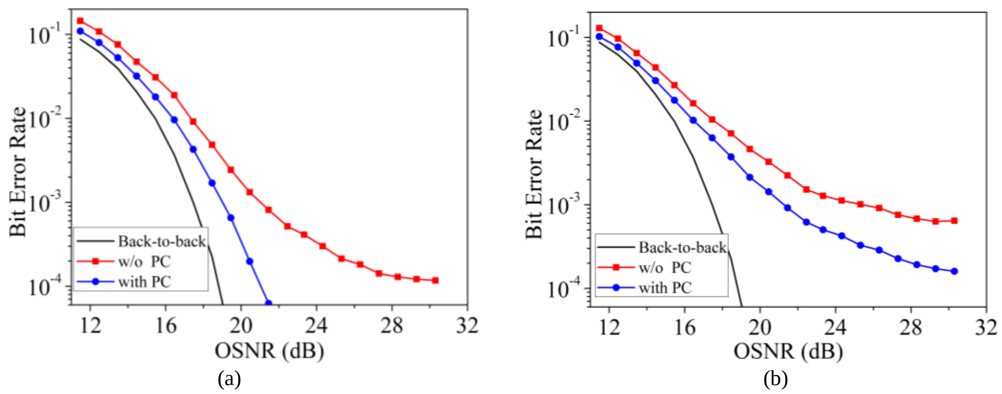


Fig. 6. Carrier phase estimation using differential detection for 2000 km fiber transmission, (a) TX linewidth is 170 MHz, LO linewidth is 0Hz, (b) both TX and LO linewidth are 5 MHz. w/o: without.

6. CONCLUSIONS

In this paper, the polarization multiplexed pilot carrier is employed to mitigate the phase noise in the 28-Gsymbol/s NRZ-QPSK coherent transmission system. For the first time to our knowledge, we present the investigation of the optical pilot carrier on the cancellation of the equalization enhanced phase noise, which is the dominant phase fluctuation in the long-haul fiber transmission system. Simulation results demonstrate that by using the optical pilot carrier, the normal laser phase noise can be eliminated significantly, while the equalization enhanced phase noise can only be mitigated slightly.

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