Analysis of Partial Pilot Filling Phase Noise Compensation for CO-OFDM Systems

Saleh Hussin, Kidsanapong Puntsri, and Reinhold Noé

Abstract—**In coherent optical orthogonal frequency division multiplexing (CO-OFDM) systems, phase noise of transmitter and local oscillator lasers has an important impact on system performance. In this letter, a partial pilot filling compensation scheme is analyzed and compared to conventional common phase error compensation and RF-pilot-based phase noise compensation. The effects of phase noise for various laser linewidths and of received optical power on system performance are evaluated. A CO-OFDM transmission system with 4-QAM is simulated with VPI transmissionMaker V8.7.**

Index Terms—**Optical fiber communication, orthogonal frequency division multiplexing (OFDM), phase noise, quadrature amplitude modulation (QAM).**

I. Introduction

ORTHOGONAL frequency division multiplexing (OFDM) is a modulation technology which is used in many broadband wired and wireless communication systems to combat multipath fading. CO-OFDM systems have recently been proven to be an appropriate modulation format for high speed optical communication [1]. It has been proposed for mitigation of chromatic dispersion (CD) [2] and polarization mode dispersion (PMD) [3]. The most important drawback of CO-OFDM is the high sensitivity to phase noise induced by transmitter and local oscillator (LO) lasers. Laser phase noise causes a common phase error (CPE) which affects each subcarrier phase and rotates the constellation points. Inter-carrier interference (ICI) is a complex value generated from laser phase drift which is added to each subcarrier sample and appears as a Gaussian noise [4], [5].

To compensate laser phase noise, the CPE (pilot-aided) and data-aided phase estimation methods have been studied [6], [7] with a small-sized fast Fourier transformation (FFT). The RF-pilot (RFP) based phase noise compensation is another technique [8] which was proposed for a CO-OFDM transmission system with laser linewidth 100 kHz and 256 FFT. With this method, the RFP is used to avoid phase noise impairments at the receiver. To separate the RF tone completely from the OFDM spectrum, it is required to generate a guard band between the RFP signal and the OFDM sidebands. A performance analysis for the CPE and the RFP phase estimation methods have been compared [9]. Different RFP schemes to recover a clear RFP and improve the performance of the CO-OFDM system have been studied and compared [10].

The pilot-based compensation has been studied to estimate the channel response by interpolation in wireless OFDM [11]. The authors in [12] used the linear interpolation method to mitigate the ICI effects in time domain, to mitigate ICI by calculating the deterministic crosstalk from adjacent subcarriers from the variation of the CPE of following OFDM-symbols. Partial pilot filling (PPF) for phase noise compensation in CO-OFDM transmission systems is investigated in [13]. The PPF scheme uses constant pilot frequencies for phase estimation to compensate laser phase noise based on linear interpolation. In this letter, a detailed comparison among the PPF based on linear interpolation, the CPE method and the RFP phase noise compensation is given. We present simulation results of a CO-OFDM transmission system at 40 Gbps with 4-QAM format and 1024-point FFT. Furthermore, the phase noise effect for various laser linewidths on the system performance is reported.

II. Simulation Setup

The generation and analysis of the OFDM signal and system performance are simulated using VPItransmissionMaker™ V8.7. Fig. 1 shows the schematic of a CO-OFDM back-to-back transmission system using PPF phase noise compensation method. An OFDM signal with a nominal data rate of 40 Gbps is generated. This bit stream is converted from serial to parallel and then mapped with 4-QAM. The IFFT/FFT size is 1024, with 64 zeros for oversampling and 954 for the modulated data subcarriers. For phase noise compensation, 6 pilots are reserved in the PPF and the CPE schemes. In case of the RFP, a spectral gap of 6 zeros is inserted around the RFP tone. The information symbols are serialized and converted to analog electrical signals by DACs at a sampling rate of 25 GS/s. A low-pass filter (LPF) is utilized to remove the aliasing. A laser with 100 kHz linewidth is modeled to generate a continuous signal at 193.1 THz. This is modulated with the OFDM signal in a null-biased IQ-MZM for CO-OFDM. To evaluate an optical signal to noise ratio (OSNR) performance, an amplified spontaneous emission (ASE) noise is added to control the received OSNR. We assume equal linewidths for transmitter and LO lasers. The LO power is assumed to be 0 dBm.

At the receiver, a homodyne detector is implemented. The OFDM signals from the balanced detectors are filtered by a LPF and then sampled with ADCs at a sampling rate

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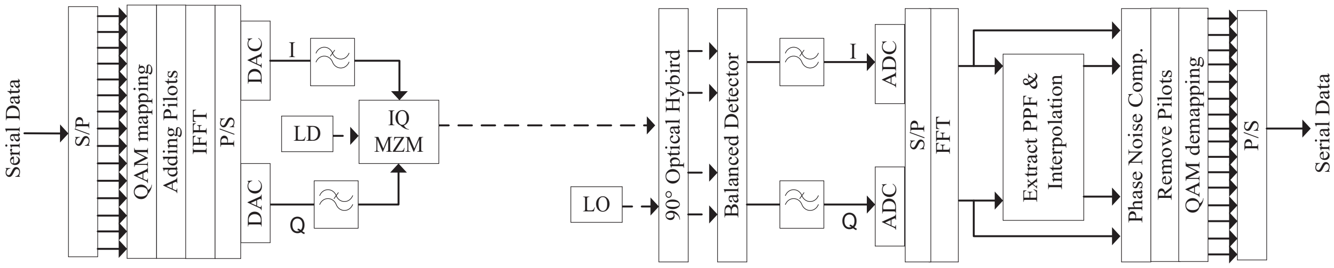

Fig. 1. Schematic for a CO-OFDM transmission system.

of 25 GS/s. The serial digital signal is converted to complex parallel data blocks by an S/P converter. An FFT demodulates the OFDM signal. Phase noise is compensated in the applied PPF schemes by separating pilots from the OFDM signal and then interpolating between two consecutive pilots to estimate the phase for OFDM subcarriers that are located between them. After a complex conjugation it multiplies with the recovered OFDM signal. After removal of the pilots each QAM symbol is decoded by QAM de-mapping to produce parallel data. They can be converted to serial data by P/S conversion.

In the PPF scheme, we assign redundant pilots to certain OFDM subcarriers. We define a filling factor (FF) as the number of pilots divided by total number of the subcarriers in each OFDM symbol which equal to OFDM subcarriers plus pilots [14].

In the CPE estimation [6] N_p uniformly distributed pilots are transmitted with the N_{sc} data subcarriers of OFDM spectrum. At the receiver, the estimated laser phase drift is calculated by computing the average of the difference between the received and the transmitted pilots for each symbol in frequency domain. The main drawbacks of this method are that OFDM frames must be short to set that the phase error effect is common for all subcarriers within an OFDM symbol.

The RFP phase noise compensation technique is able to compensate the laser phase noise by inserting an RFP tone in the middle of the transmitted OFDM signal. This can be done by setting the first element on the OFDM frame to 0 and applying a small DC offset at the I/Q components. At the receiver, the received RFP is selected by LPF. After a complex conjugation it is multiplied with the received OFDM signal to compensate for phase distortion. The zeros are padded to shift the alias which is generated by the sampling process away from the OFDM signal. It is important to optimize the pilot-to-signal ratio (PSR). The PSR is the power ratio between electrical RFP signal and OFDM signal. For low PSR, the filtered RFP is not accurate for estimating phase distortion due to the dominating ASE on the RFP tone. For high PSR, the OSNR between OFDM data and noise becomes small, which leads to worse performance. In [9], the authors analyzed and compared the CPE and the RFP phase estimation methods. They found that the RFP is more suitable for large laser linewidths and provided a fast phase dynamic. Moreover, it can compensate ICI. The main disadvantage of this method is that the residual received RFP is distorted by the received OFDM sidebands. To separate the RF tone completely from the OFDM spectrum, zeros are inserted also at both edges of IFFT input sequence which generate a guard band between the RFP signal and the OFDM sidebands. This scheme is called enhancement-RFP (E-RFP) model. The LPF can simply separate a clear, undistorted RFP [10]. The performance of the system depends on the bandwidth of the LPF, the power of the pilot tone and the number of padded zeros as the more zeros are added, the more spectral efficiency and bit rate will decrease.

III. Simulation Results and Discussion

In this section, the performances of the phase noise mitigation schemes are simulated and compared for CO-OFDM back-to-back transmission systems. An OFDM signal with a nominal data rate of 40 Gbps is generated. An IFFT/FFT size of 1024 is used with 954 OFDM data subcarriers and 0% of a cyclic prefix. A bit error ratio (BER) is simulated for each laser having a linewidth of 100 kHz and a received optical power (ROP) of 0 dBm. The E-RFP phase noise compensation models use the optimal PSR value of −15.2 dB. A 4^{th} order 35 MHz Butterworth LPF is used at the receiver side to extract the RFP signal.

Fig. 2 presents the BER performance as a function of OSNR. The required OSNR for BER of 10^{-3} is 9.6 dB, 10.0 dB and 10.7 dB for the PPF, the CPE and the E-RFP phase noise compensation algorithms, respectively. The PPF can improve OSNR at a BER of 10^{-3} by 1.1 dB compared to the E-RFP and about 0.4 dB compared the CPE method.

Fig. 3 shows the system Q factor of the received data as a function of individual laser linewidth at 10 dB of OSNR and 0 dBm ROP. The system Q factor for a linewidth of 100 kHz is 10.06 dB, 9.76 dB and 9.3 dB for the PPF, the CPE and the E-RFP phase noise compensation algorithms, respectively. In all schemes, Q factor decreases for laser linewidths beyond 100 kHz. The PPF with FF = 1/160 can improve the Q factor by 0.3 dB and 0.76 dB compared to the CPE and the E-RFP schemes, respectively. Increasing the laser linewidth up to 1 MHz brings the CPE performance close to that of the E-RFP model while the PPF method still has the best performance. The PPF scheme performs better than the CPE and the RFP schemes.

In Fig. 4, the influence of ROP on the system Q factor is shown for 40 Gbps CO-OFDM transmission systems with 10 dB of OSNR and 100 kHz laser linewidth for the E-RFP schemes, the CPE method and the PPF model. The ROP is

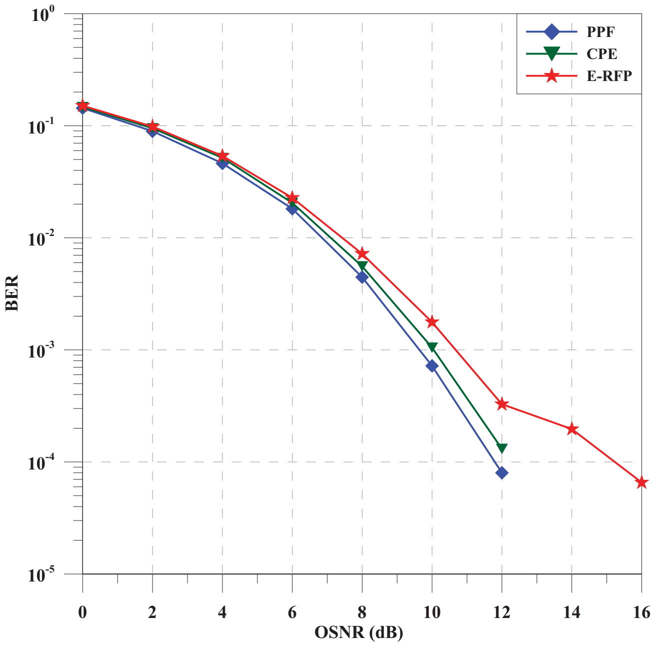

Fig. 2. BER versus OSNR.

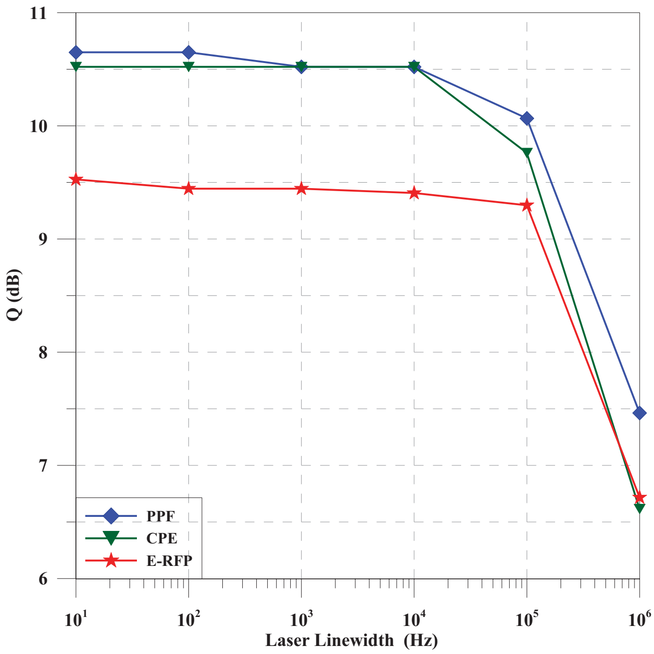

Fig. 3. Q versus laser linewidth.

varied from −40 dBm to +10 dBm. Obviously this would require automatic gain control in practice. By increasing the ROP the Q factors of the received data improve until the ROP reaches −23 dBm, then they barely change. At 0 dBm ROP, the Q value for the PPF, the CPE and the E-RPF phase noise compensation algorithms are 10.06 dB, 9.76 dB and 9.3 dB, respectively. The PPF can improve the Q factor by 0.76 dB compared to the E-RFP scheme and about 0.3 dB compared to the CPE method. The PPF method shows a better sensitivity than the E-RFP phase noise compensation and the CPE method.

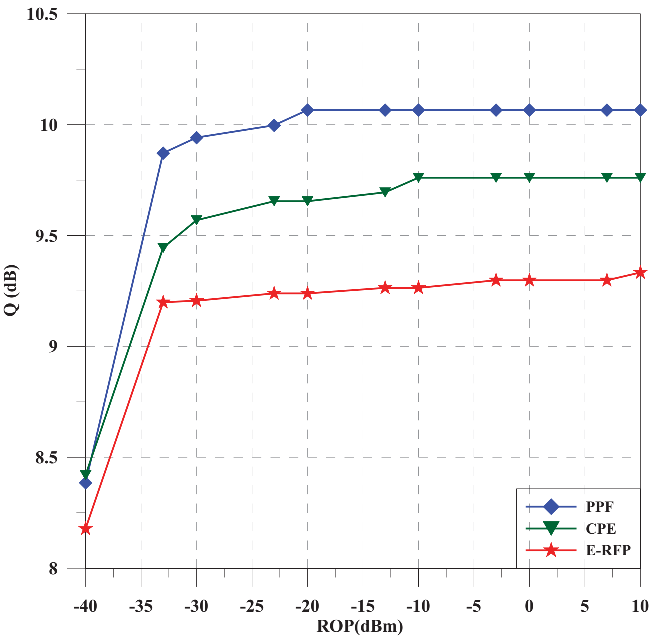

Fig. 4. Q versus ROP.

IV. Conclusion

In this letter, it has been shown that the PPF phase noise compensation scheme using constant pilot frequencies based on linear interpolation is an effective method to compensate for laser phase noise in the CO-OFDM transmission systems. Applied to a 40 Gbps CO-OFDM transmission system with 4-QAM, simulation results reveal that using the PPF method, the OSNR can be improved. Also, the PPF method can improve the Q factor at an individual laser linewidth of 100 kHz. The simulation results show that the PPF technique is robust against laser phase noise for 4-QAM CO-OFDM with 1024-FFT. It has a better sensitivity than the E-RFP model for phase noise compensation and the CPE method.

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