Pilot-aided Sampling Frequency Offset Compensation for Coherent Optical OFDM

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Abstract: A sampling frequency offset compensation based on pilot-aided phase noise mitigation scheme is proposed. SFO tolerance up to 1000 ppm for CO-OFDM is shown. An estimation deviation of 0.5 ppm is observed.

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1. Introduction

Coherent detection optical orthogonal frequency division multiplexing system (CO-OFDM) is a promising multicarrier modulation technique for future optical transmission systems. The combination of coherent detection and OFDM improves the system robustness to channel dispersion and eases the channel and phase estimation [1]. CO-OFDM is however sensitive to laser phase noise (PN) and frequency offset (FO). For PN compensation, many algorithms have been introduced such as common phase error estimation (CPE) based [2] and RF-pilot [3] based phase noise compensation. Among these, RF-pilot aided phase noise compensation shows a superior tolerance to phase noise independent of the symbol length. In recent research on phase noise compensation, a novel pilot subcarrier based structure has been proposed in [4], where additional pilot subcarrier bands are introduced to perform fine phase noise compensation for large constellation size [5].

Besides PN and FO, sampling frequency offset (SFO) between transmitter and receiver also has a great impact on the performance of CO-OFDM. However, in most of the experiments, SFO is usually neglected or highly reduced by either carefully tuning RF-sources or by using expensive RF sources. In real scenario, even a small amount of SFO seriously degrades the OFDM system performance as shown in [6]. One approach for SFO compensation could be via the use of specific training symbol structure [7]. In this work, however, the pilot-based phase noise mitigation scheme proposed in [4, 5] is extended to compensate for SFO by taking advantage of these additional pilot subcarrier bands. Simulation results show that with the proposed algorithm, standard SFO (200 ppm) for optical transmission systems can be accurately estimated and compensated. Additionally, with an allowable penalty of 1 dB, the SFO tolerance of up to 1000 ppm for 4-QAM OFDM signal is observed.

2. Simulation Setup

The structure of the transceiver is illustrated in Fig. 1. A signal transmission with PDM CO-OFDM is simulated with nominal data rates of 70.2 Gb/s for 4-QAM and 105.2 Gb/s for 8-QAM. Taking 11.3% overhead for training symbols, 6.8 % overhead for cyclic prefix and 10% overhead for FEC into account, the net data rates become 53.8Gb/s for 4-QAM and 80Gb/s for 8-QAM. The fast Fourier transform (FFT) size is 2048, from which 20.4 % is utilized for zero-padding, 3% for the spectral gap around the RFP, 3% subcarriers are left unmodulated for the guard

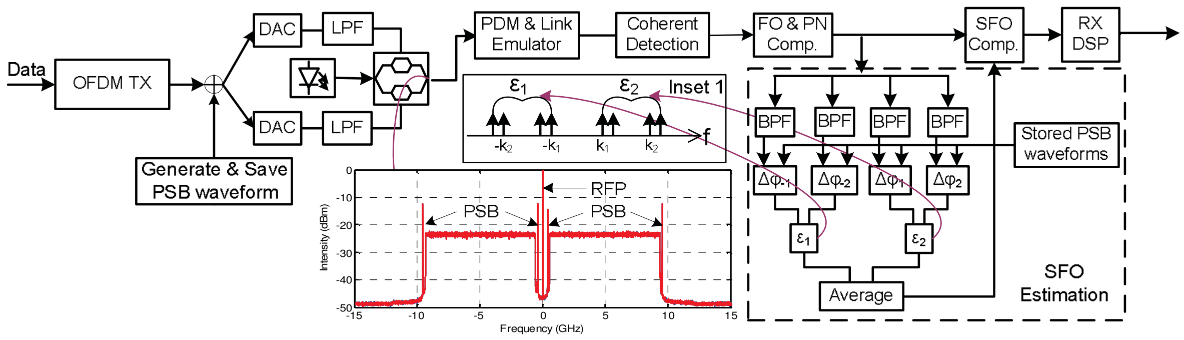


Fig. 1: Schematic for CO-OFDM transmission system. Inset1: Detail structure of SFO compensation. PDM: polarization division multiplexing; PSB: pilot subcarrier bands; PBS: polarization beam splitter

band for pilot subcarrier bands and 73.5 % for the modulated data subcarriers. A standard PDM processing is implemented in the simulation as describe in [8].

Fig. 1 shows the schematic of the CO-OFDM transmission system with the proposed SFO compensation algorithm. At the transmitter, a baseband OFDM signal and the pilot subcarrier bands (PSB) are generated separately. PSB are generated and appended symmetrically to the DC component in OFDM signal spectrum as shown in the spectrum in Fig. 1. Finally, the RF-pilot is inserted at DC component of the signal spectrum at the modulation stage. In PDM and Link emulator, the ASE noise, phase noise, frequency offset, polarization crosstalk and sampling frequency offset are added on the generated signal.

At the receiver, after coherent detection, first the RF-pilot in the central frequency of OFDM signal spectrum is filtered out for the compensation for frequency offset and phase noise [3, 4]. Next, the SFO estimation is performed as depicted in “SFO estimation” block in Fig. 1. First the PSB are filtered out with the help of band-pass filters (BPF). The centre frequency of the BPF for PSB at high frequency is designed to be adaptive by detecting the power intensity in frequency domain. The filtered PSB are then compared with the stored original waveform. The phase differences are denoted as $\Delta\varphi_n$, where n = ±1, ±2 are the band number. By comparing the phase distortions between $\Delta\varphi_1$ & $\Delta\varphi_2$ and $\Delta\varphi_{-1}$ & $\Delta\varphi_{-2}$, two SFO estimates ε_1 and ε_2 are generated as

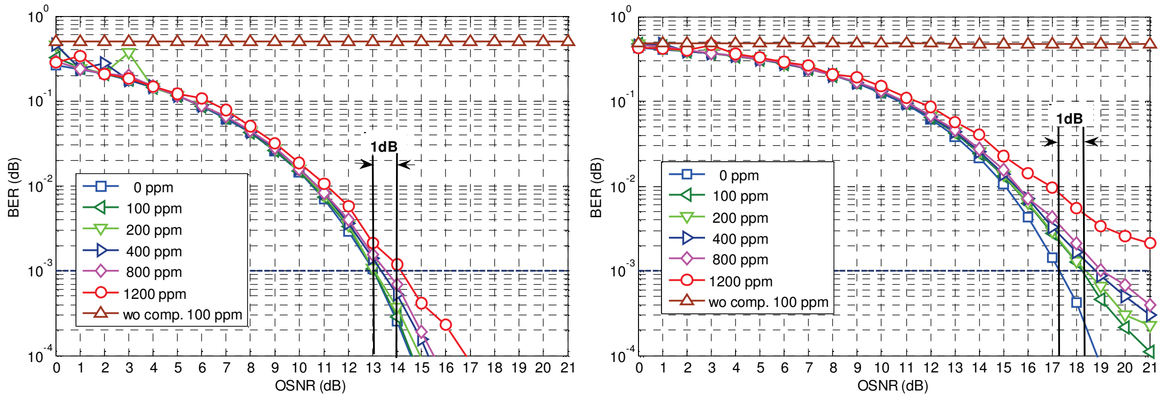
$$\varepsilon_1 = \frac{d(\Delta\varphi_2(t) - \Delta\varphi_1(t))}{dt} \times \frac{N}{2\pi(k_2 - k_1)}, \tag{1}$$

$$\varepsilon_2 = \frac{d(\Delta\varphi_{-2}(t) - \Delta\varphi_{-1}(t))}{dt} \times \frac{N}{2\pi(k_{-2} - k_{-1})}, \tag{2}$$

where, N is the FFT size, $k_{\pm1}$ and $k_{\pm2}$ represents the subcarrier index as shown in Inset 1 of Fig. 1. Since pilot subcarrier bands are used, $k_{\pm1}$ and $k_{\pm2}$ actually represents the starting subcarrier index number of each band. Finally ε_1 and ε_2 are averaged and the final estimated SFO is forwarded to SFO compensation block. A time domain sample interpolation using this SFO estimate is applied for compensation. The SFO compensated signal is then processed in RX DSP to get the BER performance.

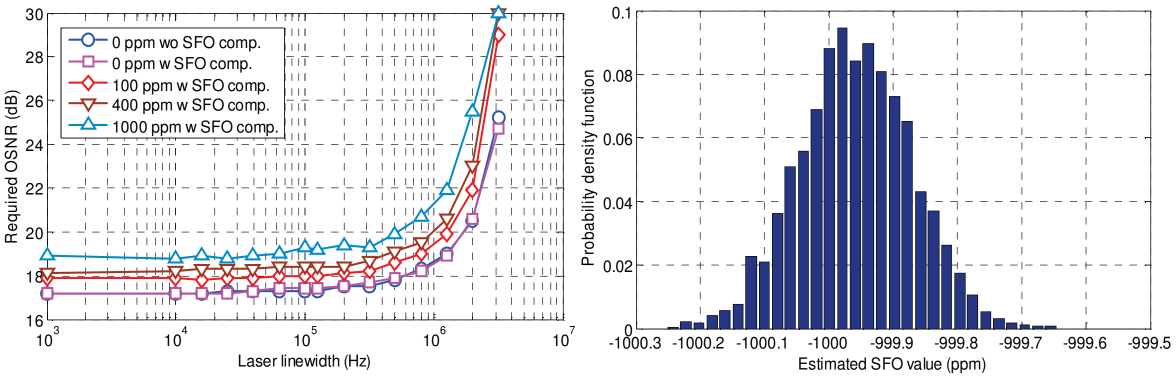
3. Simulation Results and Discussion

In this section, the performance of the PSB based SFO compensation scheme is evaluated. First, the tolerance of SFO compensation for different constellation sizes is investigated. Fig. 2(a) and 2(b) show the BER performance as a function of received OSNR for 4-QAM and 8-QAM, respectively. The SFO in these plots varies from 0 ppm to 1200 ppm. The laser linewidth is 100 kHz (conventional ECL linewidth) and 1GHz frequency offset is assumed between transmitter and receiver. Without SFO compensation (△), a BER of 0.5 is observed for a SFO of 100 ppm which is independent of the received OSNR. This clearly demonstrates the need for SFO compensation. For reference, the BER curve for the case without the introduction of SFO is plotted (□) and the required OSNR for a target BER of 10^{-3} is observed at 13 dB. Allowing a 1-dB penalty in required OSNR, a maximum tolerable SFO is found to be 1000 ppm for 4-QAM. Clearly, with PSB based SFO compensation, the SFO tolerance is greatly



(a) 4-QAM (b) 8-QAM

Fig. 2: SFO tolerance with 100 kHz laser linewidth and 1GHz frequency offset for (a) 4-QAM (b) 8-QAM



(a) Phase noise tolerance

(b) Estimates probability density function

Fig. 3: (a) The phase noise tolerance with SFO compensation scheme comparison; (b) the probability density function of the SFO estimates for 1000 ppm and OSNR 17 dB.

improved. Similarly, for 8-QAM OFDM signal, the required OSNR for no SFO was 17.4 dB. With the 1-dB allowable required OSNR penalty in the case of 8-QAM, the tolerable SFO is 200 ppm. This performance degradation can be explained by the fact that higher constellation size is more sensitive to phase distortion. For standard optical transmission systems, a SFO of 200 ppm is usually considered. For such a value of SFO, no penalty for 4-QAM OFDM system is observed.

Furthermore, the tolerance with respect to laser phase noise for different SFO is investigated. Fig. 3(a) shows the required OSNR for a target BER of 10^{-3} as a function of laser linewidth. For the cases of 0 ppm with (□) and without (○) the SFO compensation, the performances show same behavior, which indicate that this SFO estimation algorithm does not cause any additional imperfections. In the presence of SFO, there is a shift in the required OSNR which is dependent on the amount of SFO. However, this shift is almost constant even when the laser linewidth is increased. The required OSNR penalties for different SFO cases compared to no SFO are 0.7 dB, 0.9 dB and 1.7 dB for SFO of 100 ppm, 400 ppm and 1000 ppm, respectively.

Finally, to investigate the accuracy of the PSB based SFO estimation algorithm, a probability density function (PDF) of the estimated values is presented. A SFO of 1000 ppm is applied to an 8-QAM OFDM signal, with 100 kHz laser linewidth. The OSNR is fixed to 17 dB. 3000 samples are evaluated for reliable statistic PDF result. From the figure, the maximum deviation of the estimates against 1000 ppm is only 0.5 ppm (0.05%), compared to 25% maximum deviation shown in [7].

4. Conclusion

In this paper, an extension of pilot-based phase noise mitigation scheme to compensate for SFO compensation is proposed. Simulation results show that for 4-QAM OFDM system, a SFO tolerance of 1000 ppm within 1-dB required OSNR penalty is observed. The maximal variance of the SFO estimation is 0.05%.

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