Experimental Demonstration of Data-dependent Pilot-aided Phase Noise Estimation for CO-OFDM

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Abstract: We demonstrate a novel phase noise estimation scheme for CO-OFDM, in which pilot subcarriers are deliberately correlated to the data subcarriers. This technique reduces the overhead by a factor of 2.

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1. Introduction

Coherent optical frequency division multiplexing (CO-OFDM) has been considered as a promising candidate for long-haul optical communication systems because of its high spectral efficiency and excellent tolerance towards fiber chromatic dispersion and polarization mode dispersion [1]. However, CO-OFDM is sensitive to laser phase noise due to its long symbol duration. The impact of laser phase noise will introduce both common phase error (CPE) and intercarrier interference [2], which significantly degrades the system performance. Therefore, it is crucial that the laser phase noise is rigorously tracked, estimated and effectively compensated.

Existing CO-OFDM phase noise compensation (PNC) may be divided into three groups, data aided (DA) [3-5], pilot subcarrier aided (PA) [6], and radio frequency (RF)-pilot enabled estimation [7]. RF-pilot enabled estimation is realized by inserting a RF-pilot tone in the middle of the OFDM band that can be used at the receiver to revert phase noise related impairments [7]. Among these methods PA is the most widely used method due to its inherently low complexity and high precision, but at the expense of additional overhead. In this work we propose and experimentally demonstrate a novel PNC scheme termed quasi pilot-aided (QPA) phase noise compensation. The QPA method retains the use of pilot subcarriers (PSs) at known frequencies to estimate the carrier phase; however, unlike the conventional PA scheme where pilot phases are predetermined, the pilot phases in QPA depend on an associated data channel. The major advantage of QPA estimation is that the number of PSs required for a given performance can be reduced by a factor of 2 without significant additional complexity. The effectiveness of the proposed method is demonstrated by comparing with common methods, including PA and RF estimation.

2. Proposed PNC technique for CO-OFDM

By assuming a perfect FFT window synchronization and frequency offset compensation, the received OFDM signal $R_{m,k}$ can be expressed as [4]:

$$R_{m.k} = S_{m,k} h_k \exp(j\Phi_m) + \varepsilon_{m,k} + n_{m,k}\ , \tag{1}$$

where $S_{m,k}$ is the modulated data of the k^{th} subcarrier in the m^{th} symbol before transmission, h_{k} is the transmission channel response for the k^{th} subcarrier, Φ_{m} is the CPE for the m^{th} symbol due to laser phase noise or phase shifts acquired during optical fiber transmission, $\varepsilon_{\text{m,k}}$ represents residual inter channel interference and is generally treated as white Gaussian noise provided that a large number of OFDM subcarriers are used and the random Gaussian noise is represented by $n_{m,k}$.

By transmitting a few PSs along with data subcarriers, the CPE can be estimated at the receiver by averaging the phase drifts across all PSs. In PA the CPE estimate can be expressed as [6]:

$$\Phi_m = \sum_{k=1}^{Np} \left(\arg(R_{m.k}) - \arg(S_{m,k}) \right) / Np\ , \tag{2}$$

where arg(.) is the phase angle of the information symbol, $S_{\text{m,k}}$ is the known transmitted pilot symbol and N_p is the number of PSs.

It can be seen clearly in (2) that the accuracy of PA phase estimation technique is improved by increasing the number of PSs at the cost of proportionally increasing the overhead and so reducing the net data rate. Here we propose that the effectiveness of PA phase estimation may be doubled by modulating each PS with a data signal directly related the signal on a data carrying subcarrier, rather than setting each pilot to a fixed predetermined state. As the pilots are no longer constant, we term this scheme quasi-pilot aided. We consider two specific examples of QPA based estimation. In the first QPA scheme (QPA-1), all N_p pilot subcarriers are allocated in the first part of the

OFDM band, taking the central (DC) subcarrier as a reference (*k=0*). N_p pilot subcarriers (with $k=k_1, k_2,...k_{Np}$) are chosen with phases satisfying the condition: $S_{m,k}=S^*_{m,-k}$, where $*$ stands for the complex conjugate operation. That is, each pilot subcarrier is the complex conjugate of the data carrying subcarrier equally spaced from the central reference. At the receiver each pilot subcarrier is coherently combined with its data carrying counterpart, eliminating the data modulation and enhancing the signal to noise ratio. The overall CPE is then estimated by summing the resultant modulation free vectors and taking the argument, as shown in the following expression:

$$\Phi_m = \arg(\sum_{k=1}^{Np} R_{m,k} \cdot R_{m,-k}) / 2 \, , \tag{3}$$

This simple approach allows the CPE to be estimated without any prior information on the phases of PSs. In addition to this, the CPE is calculated by taking into account $2N_p$ subcarriers, which includes the complex conjugate pilots in the first half and the actual data in the second half of the OFDM band. Note that the optical signal to noise ratio (OSNR) penalty associated with transmission of the phase reference is offset by the coherent addition of the two quasi-pilots. Thus, the accuracy of this estimation is similar to the PA phase estimation scheme whilst averaging the noise $n_{m,k}$ over $2N_p$ PSs. Alternatively for a given level of performance, our proposed technique can reduce the overhead by a factor of 2, since half of the pilots carry information signals.

In the second QPA scheme (QPA-S2) instead of coding the pilots as direct conjugates of a single data subcarrier, the phases of N_p PSs are chosen such that their mean phase angle is opposite that of all the remaining data subcarriers, as specified by the condition:

$$\left\langle \arg(S_{m,k}) \right\rangle_{pilots} + \left\langle \arg(S_{m,l}) \right\rangle_{data} = 0 \, , \tag{4}$$

where $\langle \cdot \rangle$ stands for the averaging operation. Herein, the requirement (4) is satisfied by setting the phases of PSs equal by the condition: $\arg(S_{m,k}) = -<\arg(S_{m,l})>_{data}$. In this case at the receiver, the CPE is estimated by summing the phases of all pilots and associated data subcarriers according to:

$$\Phi_m = \left(\left\langle \arg(R_{m,k}) \right\rangle_{pilots} + \left\langle \arg(R_{m,l}) \right\rangle_{data} \right) / 2 \, , \tag{5}$$

Again the CPE is calculated without any a-priori knowledge about the transmitted phases of pilot subcarriers and the tolerance to noise of the CPE estimation is improved by taking all the subcarriers into consideration. As the total phase of all symbols is constant, QPA-2 may be considered as a form of “phase parity”.

In common with other techniques, the phase noise tolerance of QPA PNC methods can also be increased by using the information from the previous symbol [5]. The received samples of one symbol are compensated for the estimated CPE of the preceding symbol. Then the change in CPE between the symbols ($\Delta\Phi_m = \Phi_m - \Phi_{m-1}$) is estimated using expression (3) or (5).

3. Experimental set up

The experimental set up is illustrated in Fig. 1. The transmitter consisted of a 1553.47 nm fiber laser (100Hz linewidth); an IQ modulator biased at null point and 90^0phase offset; a 2 channel 25GS/s arbitrary waveform generator (AWG) programmed with the OFDM signal. The OFDM signal (400 symbols each of 20.48 ns length, 2% cyclic prefix) encoded with 16QAM modulation format was generated offline in MATLAB using an IFFT size of 512, where 210 subcarriers were filled with data and the remainder zeros giving a line rate of 40Gb/s (36.4Gb/s after cyclic prefix and FEC overhead removed). The output of the IQ modulator was amplified by an erbium doped fiber amplifier (EDFA) and subsequently coupled into a transmission span of 20 km of single mode fiber (SMF). A short span was used to allow focus on the laser phase noise rather than other transmission impairments. After propagating through SMF, another EDFA was used for noise loading, where a 1% tap was taken for OSNR measurement. The rest of the signal was detected using a polarization diverse coherent receiver. The electrical received signals were then sampled by a real-time oscilloscope at 80 GS/s and 25 GHz bandwidth.

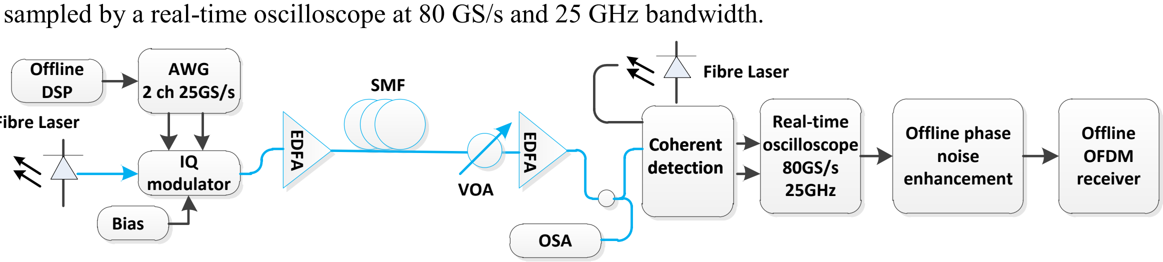

Fig. 1. Experimental Set-up (AWG: Arbitrary Waveform Generator; EDFA: Erbium Doped Fibre Amplifierr; VOA: Variable Optical Attenuator; OSA: Optical Spectrum Analyzer)

As the fiber lasers used in the experiment had a small linewidth, for investigation the impact of laser phase noise the effective linewidth was artificially enhanced by passing the received samples ($r(t)$) through a digital filter defined as: $s(t)=r(t)\cdot\exp(\theta(t))$, where $\theta(t)$ was the phase noise enhancement and followed a Wiener-Levy process [7] with a variance $\sigma^2=2\pi\cdot\upsilon\cdot dt$ where υ is the enhanced combined laser linewidth and dt is the sampling time. The offline OFDM receiver included; resampling to 25GS/s, timing synchronization, frequency offset compensation, IQ imbalance compensation, channel estimation, phase noise estimation and error counting.

4. Experimental results

The two QPA PNC schemes are compared with RF and PA methods as a function of the OSNR, as shown in Fig. 2 (a) for a combined laser linewidth of 200 kHz. The RF-pilot tone was added by detuning the IQ modulator to give a DC subcarrier (7% power) separated from the 210 data subcarriers by a frequency guard band of 100 MHz. At the receiver, the DC subcarrier was filtered out for PNC using a low pass filter with an optimised bandwidth of 20 MHz. It can be seen in Fig. 2(a) that both QPA schemes outperform the PA PNC scheme and in particular 2 pilot QPA schemes offer similar performance to 4 pilot PA schemes confirming that the overhead can be effectively reduced by a factor of 2. Similarly, 2 pilot QPA outperforms the use of an RF-pilot tone. The RF-pilot tone method is strongly affected by the size of the frequency guard band surrounding the DC subcarrier; consequently with a small overhead (1% in this paper) the QPA method outperforms the RF method. In particular, 2 pilot QPA requires a .95% overhead, which is almost equivalent to that of the RF-pilot tone.

The impact of overhead on CPE estimation performance is illustrated in Fig. 2(b), showing BER at an experimentally measured OSNR of ~26 dB. It can be seen that with the conventional PA method, 10 PSs are required for negligible penalty (less than 5% degradation in BER). On the other hand, for both QPA schemes the required number of PSs is less than 6, a reduction of almost a factor of 2.

Fig. 2(c) confirms that this advantage is maintained over a range of laser phase noises, with both 2 pilot QPA methods showing similar or enhanced performance compared to the PA method with 4 pilots for combined laser linewidths (artificially broadened) up to 800 kHz.

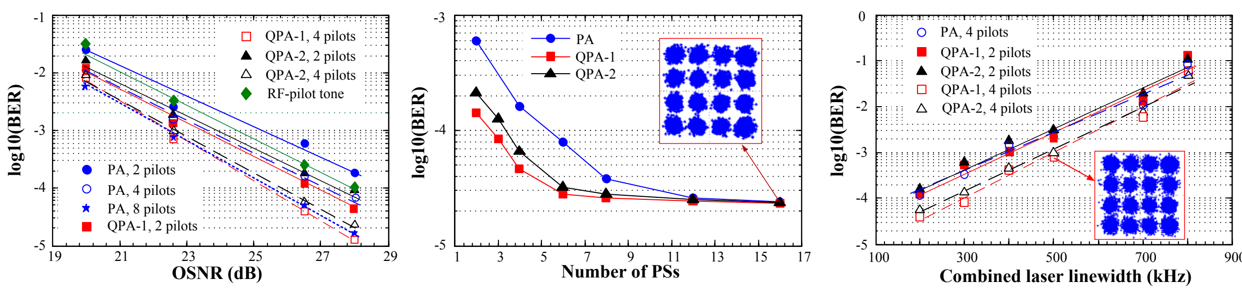

Fig. 2: Experimental results for (a) BER versus OSNR with 200kHz combined linewidth, (b) BER versus number of PSs at 26dB ONSR and (c) BER versus combined laser linewidth also at 26dB OSNR for; Green – RF pilot tone assisted estimation (RF) with 100 MHz guard band, Blue – conventional pilot aided (PA) estimation, Red - quasi pilot aided estimation using conjugate pilots (QPA-1), Black – quasi pilot aided estimation using phase parity (QPA-2) where (except in Fig. 2(b),) closed symbols represent 2 pilots, and open symbols 4.

5. Conclusion

We have proposed a novel common phase error estimation technique based on correlating the phase of pilot tones with data subcarriers. Experimental results have confirmed that by setting PSs in correlation with data subcarriers the overhead of pilot aided carrier phase estimation may be reduced by a factor of 2 for two different correlation techniques, conjugated pilots and phase parity pilots.

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