Multiplier-free Blind Phase Noise Estimation for CO-OFDM Transmission

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Abstract *We experimentally demonstrate an effective multiplier-free blind phase noise estimation technique for CO-OFDM systems for the first time based on the statistical properties of the received symbols' phases. Our technique operates in polar coordinates, providing very low implementation complexity.*

Introduction

Because of the long symbol duration, coherent optical orthogonal frequency division multiplexing (CO-OFDM) is sensitive to laser phase noise, which introduces both common phase error (CPE) and intercarrier interference. Therefore, it is crucial for CO-OFDM systems that the laser phase noise is rigorously tracked and effectively compensated.

The laser phase noise impairment can be effectively mitigated by compensating the CPE using pilot or quasi-pilot subcarriers[1]. However, such techniques reduce the spectral efficiency. To address this issue, blind phase noise compensation (PNC) techniques, such as decision-directed (DD)[2], blind phase search (BPS)[3] or the recently proposed – decision-directed-free (DDF) blind[4], can be considered. Among these techniques, DDF blind is promising due to its high performance and relatively low complexity (only three test phases are required). However, multiplications are still required, impacting the required hardware resources. As a result, a high performance, multiplier-free (MF) blind PNC technique is desirable for realizing an efficient hardware implementation, and developments have recently commenced for single carrier systems[5].

In this paper, we propose and experimentally demonstrate a novel MF blind PNC technique for QPSK and 16QAM CO-OFDM systems based on the statistical properties of the received symbols' phases. The proposed technique, while substantially simpler in implementation, offers comparable performance to other existing techniques.

MF blind PNC for CO-OFDM transmission

By assuming perfect synchronization, channel estimation and frequency offset compensation, the received OFDM signal can be expressed as:

$$R_{m,k} = |R_{m,k}|\exp(j\Phi_{m,k}) = S_{m,k}\exp(j\Phi_m) + \varepsilon_{m,k}$$

where $S_{m,k}$ is the modulated data of the kth subcarrier in the mth symbol before transmission, Φ_m is the CPE for the mth symbol due to laser phase noise and phase shifts acquired during optical fibre transmission, $\varepsilon_{m,k}$ represents residual inter-channel interference and random Gaussian noise.

In order to realize a multiplier-free system, we consider polar coordinates[6] and focus on the phase domain. It has been shown that, in the presence of fibre nonlinearity and laser phase noise, for each transmitted constellation point the received phase $\Phi_{m,k}$ is Gaussian distributed[7]. As a result, the CPE can be estimated by calculating the mean value of the received phases for each constellation point. However, this approach requires a decision directed algorithm, and thus suffers from error propagation for large phase noises. To avoid error propagation, we propose the removal of symbols with high error probabilities from the calculation. In other words, only symbols with lowest error probabilities (symbols in the interval with highest probability density or the most populated bin) should be considered. In Bayesian statistics, the most populated bin (MPB) is also referred as the credible interval.

In practical implementations, the MPB with a width of α can be estimated using a simple scanning algorithm as shown in Fig. 1, where the scanning bin is moved from the left to the right (within a predefined range) with a small scanning step of Δα ($L_{k+1}=L_k + \Delta\alpha$). At each step, the number of symbols' phases falling into

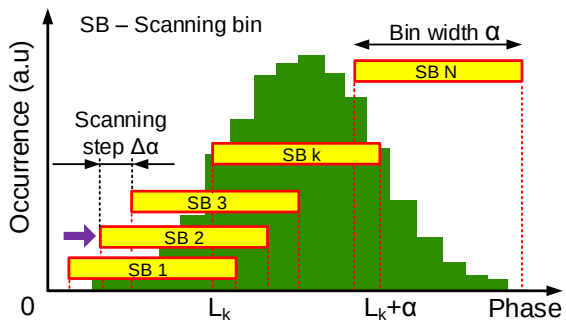

Fig. 1. Estimating the MPB with a bin width of α using the scanning algorithm with overlapping bins and small scaning

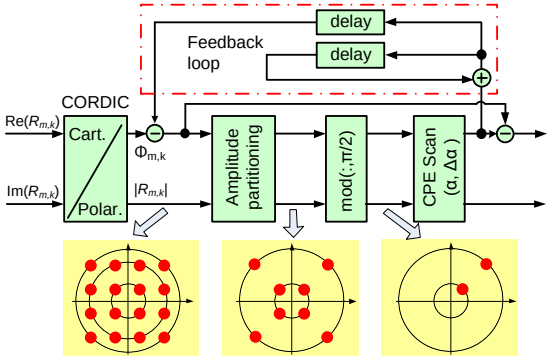

Fig. 2. Block diagram of the proposed PNC technique for 16QAM CO-OFDM systems. For QPSK the amplitude partitioning block is not needed.

the scanning bin is calcuated (P_k) and the MPB is then defined as the bin providing the largest number of samples (P_k). This algorithm requires only comparator and counting operators, thus offering very low implementation complexity.

The block diagram of the proposed MF blind PNC technique is shown in Fig. 2 for 16QAM. For QPSK signal the amplitude partitioning block can be removed. The proposed scheme can be described in 4 steps. In the first step, the receved m^{th} OFDM symbol is converted to polar coordinates using CORDIC algorithm[6], which uses only bit shifts and additions. The phases are used in all following steps while the amplitude is needed only for partitioning in the case of 16QAM, where all the information symbols from the middle ring are removed. Second, the symbols' phases are rotated using the estimated CPE of the previous OFDM symbol. This step is necessary to avoid cycle slip as blind PNC algorithms can only deal with a CPE in a range of width π/2. Next, all symbols' phases are wrapped into the interval [0, π/2] using the mod(:,π/2) function, which is performed only by comparator and addition operations. Finally, the MPB is estimated and the residual CPE is then calculated as the mean value of the symbols' phases in the MPB as:

$$\Delta\Phi_m = \Phi_m - \Phi_{m-1} = \underset{\Phi_{m,k} \in MPB}{mean}(\Phi_{m,k} - \pi/4)$$

To achieve the best performance the bin width (α) and scanning step (Δα<α) should be optimized. If the bin width is too small, the number of symbols' phases falling in the MPB is also small and the impact of Gaussian noise can be significant. If the bin width is too big, the MPB may include symbols with high error probabilities leading to error propagation. Note that α = π/2 corresponds to the DD algorithm, performed in the phase domain. In addition, the scanning step should be small enough so the MPB can be accurately estimated, but no smaller than necessary to minimize complexity.

Typical optimization results for (α, Δα) are shown in Fig. 3 for a 16QAM CO-OFDM system with 210 subcarriers and a symbol duration (Ts) of 20.48 ns in the back-to-back case. The optimum value of bin width is found to be ~ π/8 while Δα can be as large as 0.15 for a value of

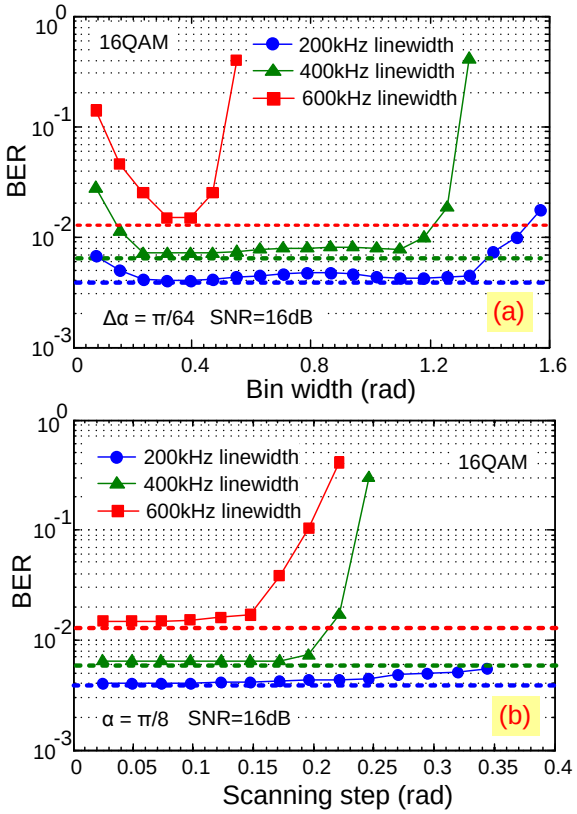

Fig. 3. Impact of α and Δα on the performance of MF bind PNC technique in 16QAM CO-OFDM transmissions in back-to-back case. The dash lines show the BER performance when the CPE is perfectly compensated.

Δf up to 600kHz. At this optimum value of bin width, the proposed technique shows almost no penalty (less than 5% degradation in log10(BER)) in comparison to the case where the CPE is perfectly compensated by using all subcarriers as pilots (showed as dash lines in Fig. 3) for all linewidths considered. This result clearly indicates the high performance of the proposed technique.

Experimental setup and results:

The experimental set-up is shown in Fig. 4 (a). It comprised one 100 kHz linewidth and two standard DFB lasers on a 25 GHz grid. Additional loading channels (10 GHz of bandwidth, 25 GHz spacing) were generated using an ASE source which was spectrally shaped using a wavelength selective switch (WSS). The twenty loading channels were spread symmetrically around the test wavelengths so that the total bandwidth of the transmitted signal was 575 GHz. The transmission path was re-circulating loop consisting of a single span 100 km Sterlite OH-LITE (E) fibre, having around 19 dB insertion loss. A gain flattening filter was placed in the mid stage of the EDFA. After propagation the centre channel was coherently detected. The OFDM signals (400 symbols each of 20.48 ns length, 2% cyclic prefix) encoded with QPSK or 16QAM were generated offline in MATLAB using an IFFT size of 512, where 210 subcarriers were filled with data and the remainder with zeros, thus giving line rates of

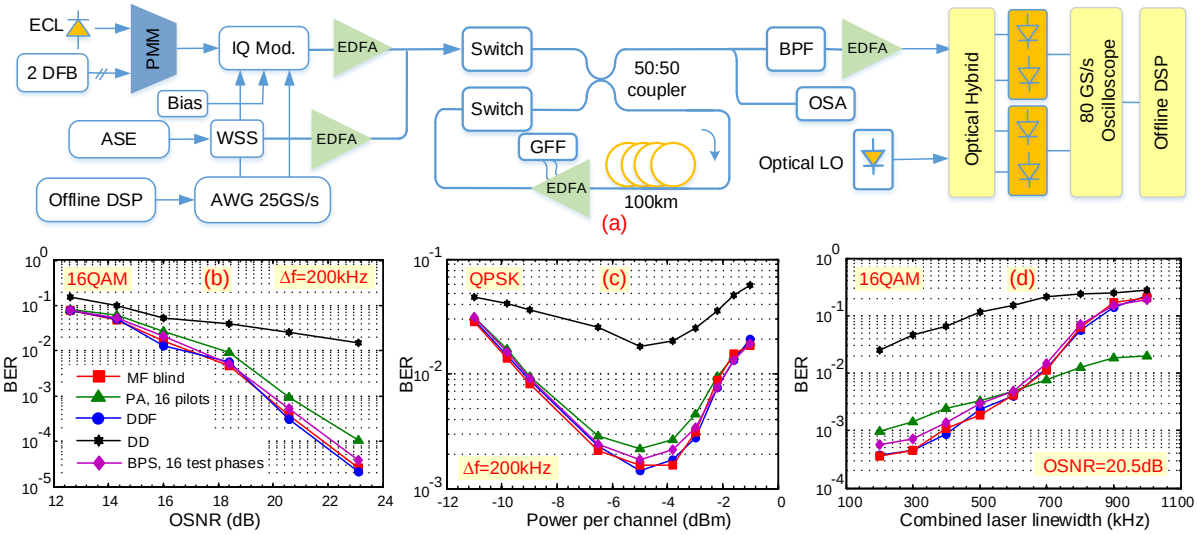

Fig. 4 (a) - Schematic of experimental setup of WDM CO-OFDM. ECL: external cavity laser, PMM: polarization maintaining multiplexer, WSS: Wavelength Selective Switch, DFB: distributed feedback laser, BPF: band-pass filter (optical), GFF: gain flatten filter, OSA: optical spectrum analyser, LO: local oscillator. Experimental results for (b) – BER versus OSNR in back-to-back case for 16QAM, (c) – BER versus power for QPSK transmission over 4000 km, (d) – BER versus combined laser linewidth for 16QAM transmission in back-to-back case.

20 Gb/s (18.2 Gb/s net data rate, after 7% FEC overhead removal) and 40 Gb/s (36.4 Gb/s net), for QPSK and 16QAM respectively. For investigating the impact of laser linewidth, the effective laser linewidth was artificially enhanced by passing the received samples ($r(t)$) through a digital filter defined as: $w(t) = r(t)\exp(\theta(t))$, where $\theta(t)$ was the phase noise enhancement and followed a Wiener-Levy process with a variance $\sigma^2 = 2\pi\nu\delta t$ where ν is the enhanced combined laser linewidth and δt is the sampling time. The offline OFDM receiver included; resampling to 25GS/s, timing synchronization, frequency offset and IQ imbalance compensation, chromatic dispersion compensation using an overlapped frequency domain equalizer with the overlap-and-save method, channel estimation with the assistance of an initial training sequence (2 training symbols every 100 symbols), PNC and error counting. The BER was obtained by processing 10 recorded traces (~10^6 bits).

The proposed PNC scheme is compared with two-stage blind DD, DDF blind, BPS and pilot-aided (PA) methods in Fig. 4(b-d) for QPSK and 16QAM WDM CO-OFDM transmissions. In applying the proposed MF blind technique the optimisation parameters were chosen to be ($\alpha = \pi/8$, $\Delta\alpha = \pi/64$). In this case, the MPB can be selected after 24 scanning steps. For comparison, alternative PNC techniques were considered and optimized according to [2-5]. In Fig. 4(b)-(c) the proposed MF blind PNC technique outperforms PA with 16 pilots (7.6% overhead) and shows a similar performance (less than 0.5dB variation in the OSNR requirement at the BER of 10^{-3}) in comparison with highly complex BPS (16 test phases) and DDF blind. This clearly indicates that statistical digital signal processing techniques can be effectively applied for OFDM systems employing hundreds of subcarriers. In Fig. 4(d) all considered blind PNC techniques shows similar phase noise tolerance, degrading significantly if the residual CPE after the first equalization stage lies outside the range ($-\pi/4$, $\pi/4$). This indicates that the proposed MF blind PNC technique can be applied effectively, and without differential coding to systems with a combined laser linewidth up to 600 kHz ($Ts{\cdot}\Delta f{\sim}10^{-2}$).

Conclusion

We have proposed a high performance blind PNC technique for CO-OFDM which can be implemented effectively without multiplications.

Acknowledgements

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