Phase-conjugated Subcarrier Coding for Fibre Nonlinearity Mitigation in CO-OFDM Transmission

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Abstract *We demonstrate a novel subcarrier coding scheme combined with pre-EDC for fibre nonlinearity mitigation in CO-OFDM, showing that a performance improvement of 1.5 dB can be achieved in a 150 Gb/s BPSK PDM CO-OFDM transmission.*

Introduction

It is well known that the nonlinear distortion due to the Kerr effect is a major limiting factor in high speed optical communication systems[1]. Various methods including all-optical and digital signal processing (DSP) have been proposed to supress the fibre nonlinearity impairments. Digital-back-propagation (DBP) is an attractive nonlinearity compensation technique, which removes the nonlinear distortion by inverting the distorted signal at the receiver digitally[2]. However, accurate DBP requires a substantial increase in DSP complexity, proportional to the number of spans. Fibre nonlinear impairments can also be effectively mitigated using optical phase conjugators[3] (OPC). However, inserting an OPC into the links significantly reduces the flexibility of the optical network.

A breakthrough fibre nonlinearity compensation technique called phase-conjugated twin wave (PCTW) has been proposed recently by X. Liu et al[4]. In the PCTW scheme, the signal complex waveform and its phase-conjugate copy are simultaneously transmitted in x- and y-polarization states to achieve nonlinear noise cancellation at the receiver through coherent superposition of the two copies. However, PCTW halves the spectral efficiency (SE), meaning that the maximum achievable SE in a polarization division multiplexed (PDM) system with QPSK modulation format and PCTW scheme is ~2 bits/s/Hz, which is the same as those achieved in PDM BPSK transmission. To address this drawback of PCTW, a dual PCTW scheme combined with quadrature pulse shaping has been proposed[5] for single carrier systems, yielding an improvement of ~1.2 dB. Unfortunately, quadrature pulse shaping cannot be applied effectively for multicarrier modulation format such as orthogonal frequency division multiplexing (OFDM). As a result, the dual PCTW scheme is not directly beneficial for coherent optical OFDM (CO-OFDM) transmission.

In this work, we propose a novel fibre nonlinearity mitigation technique for CO-OFDM transmission by adopting the dual PCTW scheme to process neighbouring OFDM subcarriers simultaneously, providing no additional overhead. The benefit of this proposed fibre mitigation technique comes from the fact that the nonlinear distortions on neighbouring OFDM subcarriers are highly correlated as the subcarrier frequency spacing in CO-OFDM transmission is usually small (tens of MHz). Combined with the optimized pre-electronic dispersion compensation (EDC), the proposed scheme shows 1.5 dB improvement in the system's Q-factor in a 150 Gb/s PDM BPSK CO-OFDM transmission. In addition, for a 300 Gb/s PDM QPSK CO-OFDM transmission, a performance improvement of around 0.7 dB can also be achieved.

Phase-conjugated subcarrier coding for CO-OFDM
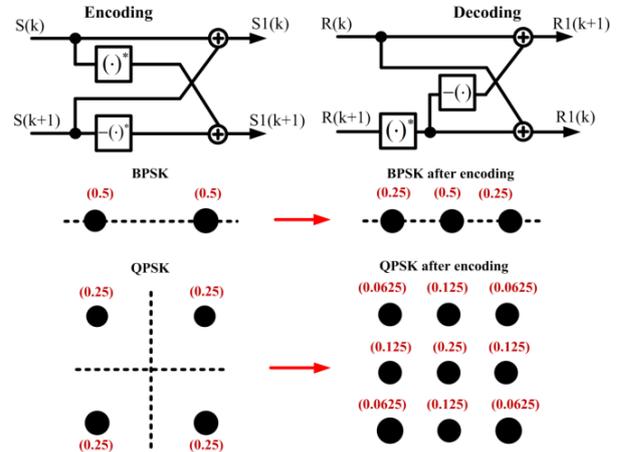

Fig. 1: The proposed phase-conjugated coding scheme for CO-OFDM transmission, the numbers (in red) are the probabilities of symbols in the constellation set

In the proposed phase-conjugated subcarrier coding (PCSC) scheme (Fig. 1) each pair of neibouring subcarriers after symbol mapping (*S(k)* and *S(k+1)*) are encoded before beeing fed into the IFFT block to generate the time-domain signal as: $S1(k) = S(k)+S(k+1)$ and $S1(k+1) = S^*(k) – S^*(k+1)$, where *(.)** stands for the complex conjugation operation. At the receiver, before symbol demapping, the
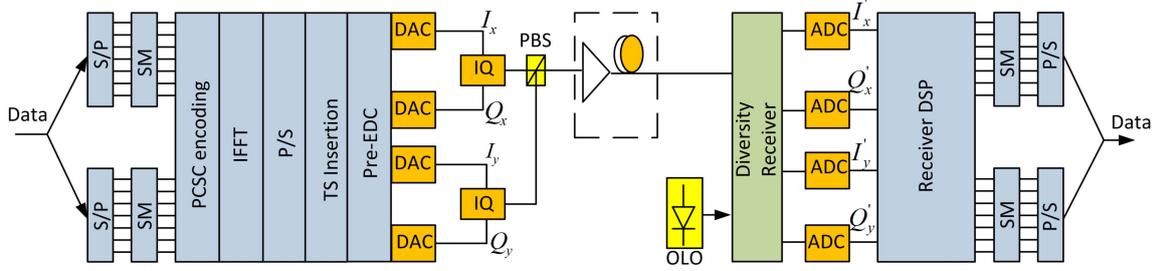
Fig. 2. Block diagram of PDM CO-OFDM transmission. S/P: serial/parallel conversion, P/S: parallel/serial conversion, SM: symbol mappings, TS: training symbol, DAC: digital-to-analog converter, ADC: analog-to-digital converter, I/Q: I/Q modulator, PBS: polarization beam splitter, OLO: optical local oscillator

received information symbols on this subcarrier pair are decoded as: $R1(k) = (R(k)+R^*(k+1))/2$ and $R1(k+1) = (R(k) - R^*(k+1))/2$. It should be noted that the PCSC scheme does not require any overhead. The only requirement of PCSC is that the number of OFDM subcarriers is even.

The proposed PCSC scheme modifies both the constellation set and probabilities of constellation points. As shown in the Fig. 1, if the input modulation format is BPSK with equal probability (0.5, 0.5) for each constellation point (-1, 1), the output constellation set will be a 3 ASK (-2, 0, 2) in which the symbol "0" occurs twice as often as the two other information symbols (-2, 2). This indicates that 50 % of OFDM subcarriers will be turned off after encoding. Similarity, if the input modulation format is QPSK, after encoding, the output constellation set will be a 9 QAM with unequal probabilities (Fig. 1), which can potentially reduce the nonlinear distortions on OFDM subcarriers due to the unequal power distribution across the OFDM band[6]. After decoding the input constellation set can be recovered.

It should be noted that the PCSC scheme does not lead to a SNR penalty or SNR advantage in a linear channel with Gaussian noise. However, in a CO-OFDM transmission, the nonlinear distortions on neighbouring subcarriers are highly correlated, and thus, performance improvement can be achieved by encoding and processing neighbouring subcarriers simultaneously at the transmitter and receiver. In order to enhance the similarity of nonlinear distortions on neighbouring OFDM subcarriers, and thus, further improving the effectiveness of PCSC, pre-EDC is applied in this work to create a dispersion-symmetry along the transmission link [4, 5].

Simulation setup and results:
The effectiveness of the proposed PCSC scheme was investigated through numerical simulation using MATLAB. Figure 2 shows the block diagram of a PDM CO-OFDM system. The data stream was first divided into x- and y-polarizations, each of which was then mapped onto 1000 subcarriers and subsequently transferred to the time domain by an IFFT of size 2048 while zeros occupying the remainder.

The OFDM useful symbol duration was 12 ns and a cyclic prefix of 0.4 ns was added for polarization mode dispersion (PMD) compensation. The net bit-rate (after extracting 7 % FEC) is 150 Gb/s and 300 Gb/s when BPSK and QPSK are adopted. The long-haul fibre link comprised 80-km spans of standard single mode fibre (SSMF) with a loss parameter of 0.2 dB/km, nonlinearity coefficient of 1.22 $W^{-1}km^{-1}$, dispersion of 16 ps/nm/km and PMD coefficient of 0.1 $ps/km^{1/2}$. The span loss was compensated by Erbium-doped fibre amplifiers with 16 dB of gain and 6 dB noise figure. The amplified spontaneous emission noise is added inline to ensure that the interaction between signal[7] and noise is correctly captured. The transmitter and receiver lasers had the same linewidth of 100 kHz. The simulated time window contained 500 OFDM symbols (10^6 bits for QPSK). The DSP at the receiver includes chromatic dispersion compensation using an overlapped frequency domain equalizer with overlap-and-save method, channel estimation and equalization with the assistance of initial training sequence (2 training symbols every 100 symbols) using zero forcing estimation with MIMO processing, common phase error compensation with pilot subcarriers (16 pilots every OFDM symbol) and symbol detection. The system performance is evaluated using the Q-factor derived directly from the BER.

Performances of the 150 Gb/s PDM CO-OFDM system with and without the proposed coding scheme are compared in the Fig. 3. In this figure the performance of PCTW technique with QPSK modulation format providing the same SE (~2 bits/s/Hz) is also presented. As PCTW haves the SE, despite the effective nonlinear noise cancellation effect, PCTW with QPSK modulation format gives only around 0.5 dB advantage over the traditional BPSK PDM CO-OFDM transmission scheme. On the other hand, when the proposed coding scheme combined with pre-EDC is applied, an improvement of 1.5 dB can be achieved without reducing the SE. Interestingly, a nonlinear noise squeezing effect was observed (Fig. 4, 5) in a similar manner as in single carrier system with real-valued signal and the symmetrical dispersion map [8]. Without PCSC, the real and imaginary
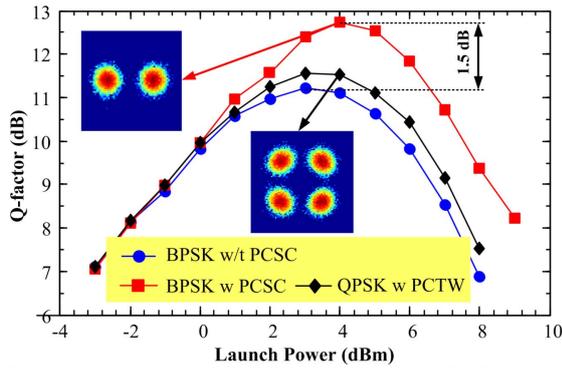
Fig. 3. Q-factor as a function of the launch in 150 Gb/s PDM CO-OFDM system with and without PCSC, after 8000 km of transmission distance
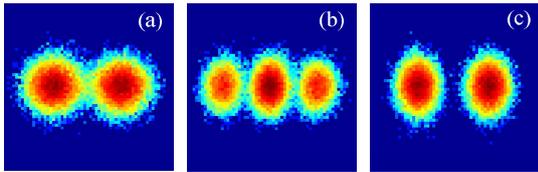

Fig. 4. Constellation diagrams on x-polarization, 8dBm of the launch power, a) – without coding, b, c) with coding, before and after decoding
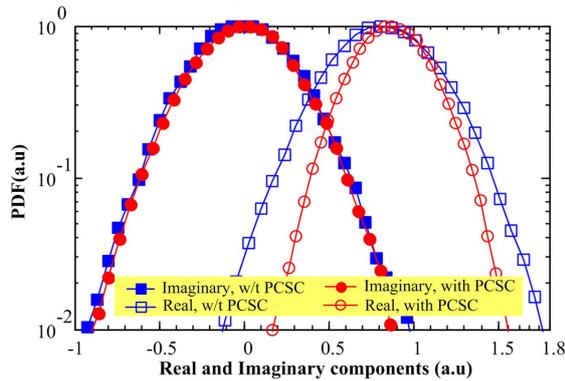

Fig. 5. PDF of real and imaginary components for the "1" symbol in systems with and without the PCSC, the launch power was 7 dBm
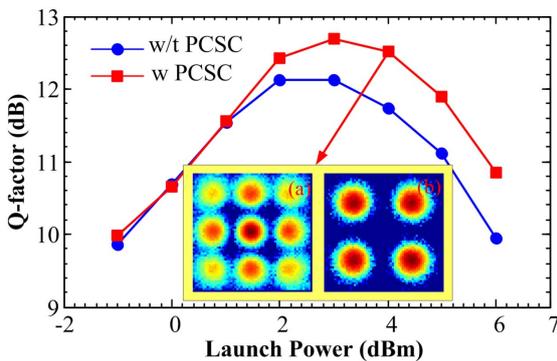

Fig. 6. Q-factor as a function of the launch power in 300 Gb/s PDM CO-OFDM system with and without PCSC and constellation diagrams (before (a) and after (b) decoding) at 4 dBm, after 3200 km of transmission distance

parts of each constellation point have the same distribution. However, with PCSC and the optimized pre-EDC, the PDF of the real part of each constellation point is significantly narrowed

while the PDF of the imaginary part seems to be unaffected (Fig. 5). This nonlinear noise squeezing effect significantly reduces the BER in a transmission system using BPSK modulation format.

When the PCSC scheme combined with the optimized pre-EDC is applied for 300 Gb/s QPSK PDM CO-OFDM system, a performance improvement of around 0.7 dB is achieved as shown in the Fig. 6. This result clearly indicates that the proposed PCSC scheme also effectively mitigates the nonlinear distortions on OFDM subcarriers when QPSK modulation format is adopted. However, as QPSK cannot take the advantage of the nonlinear noise squeezing effect, the performance improvement in this case is only a half of those achieved with BPSK modulation format.

Conclusion

We have showed that the fibre nonlinearity impairments in CO-OFDM transmission can be mitigated by processing neighboring subcarriers simultaneously. The proposed coding scheme is very simple and can be effectively combined with pre-EDC to achieve a performance improvement up to 1.5 dB.

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