Polarisation mode dispersion mitigation in coherent optical orthogonal frequency division multiplexed systems

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Coherent optical orthogonal frequency division multiplexing (CO-OFDM) to mitigate polarisation mode dispersion (PMD) in optical media is proposed. It is shown that PMD in deployed links can be overcome by CO-OFDM systems at 10 Gbit/s and beyond.

Introduction: Recently we have proposed a multi-carrier format called coherent optical orthogonal frequency division multiplexing (CO-OFDM) to combat fibre chromatic dispersion, and have shown that a CO-OFDM signal can traverse 3000 km of standard singlemode fibre without dispersion compensation [1]. In this Letter, we show another critical feature for the CO-OFDM system, namely, its extreme resilience to polarisation mode dispersion (PMD). We find that a CO-OFDM signal at 10 Gbit/s experiences no penalty through first-order PMD fibre with a differential group delay (DGD) of 700 ps, and all-order PMD fibre with a mean PMD of 150 ps. This finding is significant because it shows that the CO-OFDM system could provide a feasible solution to the mitigation of PMD in existing installed fibre links. Furthermore, the PMD mitigation with CO-OFDM is intrinsically embedded in the receiver signal processing for data demodulation, which does not require any additional complicated hardware, such as polarisation controllers and birefringence elements. We also note that incoherent optical OFDM (IO-OFDM) provides similar chromatic dispersion tolerance with a simpler detection scheme [2], but it does not provide a PMD mitigation capability.

Principle of PMD insensitivity: OFDM has been extensively investigated to combat RF microwave multipath fading, and has been widely implemented in various digital communication standards such as wireless local area network standards (WiFi IEEE 802.11a). The principle of optical OFDM is to transmit data through a large number of multiple orthogonal subcarriers [1, 2]. An OFDM signal in the time domain consists of a continuous stream of OFDM symbols with a regular period T_s, each containing observation period t_s and guard interval Δ_G. It can be easily shown that if the maximum delay spread of multipath fading is smaller than the guard time Δ_G, the cyclic prefix in the guard interval can perfectly eliminate the inter-symbol interference (ISI). In the context of optical communications, the fundamental condition for complete elimination of ISI in optical medium is given by

$$\frac{c}{f^2}|D_t|N_{sc}\Delta f + DGD_{\max} \leq \Delta_G \tag{1}$$

where f is the frequency of the optical carrier, c is the speed of light, D_t is the total accumulated chromatic dispersion in units of ps/pm, N_{sc} is the number of the subcarriers, Δf is the subcarrier channel spacing and $DGD_{\max}$ is the maximum budgeted DGD, which is about 3.5 times the mean PMD. The first and second term on the left side of (1) represent the delay dispersion from chromatic dispersion and PMD, respectively. In this Letter, for the sake of simplicity, we analyse the system for which the chromatic dispersion is near zero, and the guard time interval margin is used for PMD mitigation.

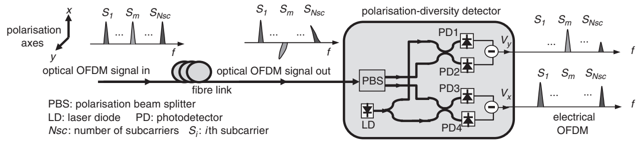

Fig. 1 *Principle of polarisation insensitivity for CO-OFDM system*

Fig. 1 illustrates the principle of polarisation insensitivity of CO-OFDM-based signals. At the input, the launched polarisation for each subcarrier is aligned, but the polarisation for each individual subcarrier will evolve differently owing to the PMD in the fibre, resulting in polarisation misalignment for individual subcarriers at the output. At the receiving end, the polarisation-diversity detector [3] decomposes the signal field into two orthogonal polarisation components, and feeds them separately into a pair of balanced detectors. The output signals from the balanced detector pairs, V_x and V_y, are subsequently processed by an electrical OFDM receiver to recover individual subcarrier symbol, e.g. c_x^{ki} and c_y^{ki} for the kth subcarrier in the ith OFDM symbol [1, 2]. Following the same procedure as in [1] and assuming that the channel spacing Δf is sufficiently narrow by selecting large observation period t_s, the channel model for OFDM signals can be shown to be given by

$$\tilde{C}'_{ki} = e^{j\phi_i}e^{j\Phi_D(f_k)}U(f_k)\tilde{C}_{ki} + \tilde{n}_{ki} \tag{2}$$

where $\tilde{C}'_{ki} = \begin{pmatrix} c_x^{ki} \\ c_y^{ki} \end{pmatrix}$ is the received information symbol in the form of the Stokes vector for the kth subcarrier in the ith OFDM symbol, $\tilde{C}_{ki}$ is the corresponding transmitted information symbol, $\tilde{n}_{ki} = \begin{pmatrix} n_x^{ki} \\ n_y^{ki} \end{pmatrix}$ is the amplified-spontaneous-emission (ASE) noise including two polarisation components, f_k is the OFDM frequency for the kth subcarrier, $U(f_k)$ is the Jones matrix for the fibre link [4], $\Phi_D(f_k)$ is the phase dispersion due to the fibre chromatic dispersion [1], and ϕ_i is the OFDM symbol phase noise due to the phase noises from the lasers and RF local oscillators (LO) at both the transmitter and receiver [1]. ϕ_i is usually dominated by the laser phase noise.

From (2), we can see that the PMD impact to a CO-OFDM subcarrier is a simple rotation of the Jones vector $\tilde{C}'_{ki}$. Therefore processing the information symbol $\tilde{C}'_{ki}$ as a two-element Jones vector on a subcarrier basis is basically an all-order PMD mitigation. As a result, PMD does not practically cause any impairment to the CO-OFDM signal. Since the receiver signal processing is on a subcarrier basis and subsequently the PMD sensitivity is only determined by the subcarrier channel spacing, instead of the number of subcarriers (N_{sc}), a higher bit rate system with the same channel spacing and a higher N_{sc} will not increase the PMD sensitivity. In contrast, in a conventional single-carrier system, the PMD impairment increases drastically with the bit rate [5]. Additionally, for IO-OFDM based systems where a main optical carrier is sent along with the OFDM subcarriers [2], the polarisation misalignment between the main carrier and the OFDM subcarriers will cause severe fading when directly detected. Therefore, unlike CO-OFDM, IO-OFDM does not provide PMD mitigation.

Simulation model and results: We performed a simulation to confirm the theoretical prediction of PMD insensitivity for the CO-OFDM system at 10 Gbit/s. The OFDM system parameters used for the simulation are a symbol period of 6.4 ns, a guard interval of 710 ps, and 64 subcarriers. BPSK encoding is used for each subcarrier resulting in total bit rate of 10 Gbit/s. The linewidth of the transmitter laser and the receiver laser are assumed to be 150 kHz each, which is close to the value achieved with commercially available semiconductor lasers. The link optical noise from the optical amplifiers is assumed to be white Gaussian noise and the phase noise of the lasers is modelled as white frequency noise characterised by their linewidth. A total number of 3200 OFDM symbols are used for each BER simulation, with the signal spanning 20.5 µs in time and containing 204 800 pseudorandom bits. The A/D sampling rate for the OFDM receiver is $N_{sc}/t_s = 11.4$ Gsample/s. The phase noise ϕ_i plus some constant offset for each OFDM symbol is estimated by averaging over the phases of 64 subcarriers and removed from the receiving symbol $\tilde{C}'_{ki}$. For symbol decision on each subcarrier, a moving window of 100 OFDM symbols is used to estimate the position of '1' and '0', each represented by a Jones vector. An error occurs when the transmitted '1'/'0' symbol in a particular subcarrier is closer to the expected '0'/'1' at the receiver. The analysis and the conclusion are equally applicable to data rates beyond 10 Gbit/s by using a larger number of subcarriers, N_{sc}.

Fig. 2 shows the BER performance of the CO-OFDM for first-order PMD mitigation, assuming equal power splitting into the two principal states. For the back-to-back configuration, a BER of 10^{-3} can be achieved at an OSNR of 3.5 dB. The OSNR penalty at a DGD of 700 ps is not measurable and the penalty at 1000 ps is below 1 dB. Compared to the best electronic compensation result using the Viterbi algorithm, which gives an OSNR penalty of 1 dB at a DGD of 50 ps [6], our approach represents more than a tenfold improvement. We also conducted the simulation with the CO-OFDM signal traversing a fibre link with a mean PMD of 150 ps, which is emulated with cascades of 96 birefringence elements and polarisation rotators that gives all-order PMD characteristics. A run of 1000 PMD realisations was performed with an OSNR of 3.5 dB. Fig. 3 shows a snapshot of the evolving DGD and second-order PMD (SOPMD) in the fibre and associated BER of the CO-OFDM signal. Fig. 3 shows that the CO-OFDM signal does not experience BER degradation passing through all-order PMD fibre. Repeated runs of different 1000 realisations yield identical BER results. Note that mitigation of a mean PMD of 150 ps may be sufficient to cover most installed links.

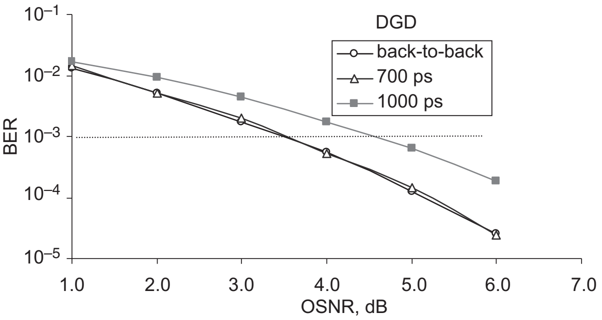

Fig. 2 *BER performance with varying first-order DGD*

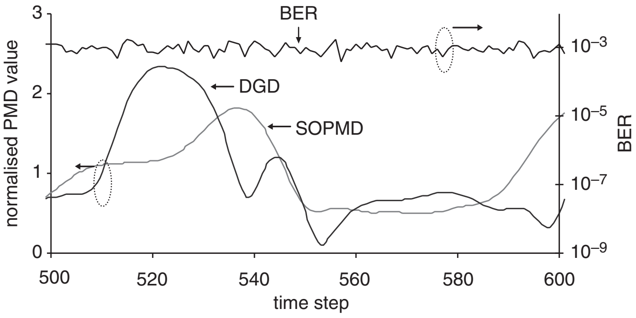

Fig. 3 *Time evolution for DGD, SOPMD and BER for CO-OFDM signal traversing a link with a mean PMD of 150 ps*

DGD and SOPMD are normalised to their mean values of 150 ps and 1.3 × 10^4 ps^2, respectively

Conclusion: We have proposed CO-OFDM to mitigate PMD in optical media. We have shown that the PMD in deployed links can be overcome by CO-OFDM systems at 10 Gbit/s and beyond.

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