# PMD-Supported Coherent Optical OFDM Systems

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*Abstract*—**Although polarization-mode dispersion (PMD) greatly impairs conventional high-speed single-carrier systems, it is shown that for multicarrier systems such as coherent optical orthogonal frequency-division-multiplexed systems (CO-OFDM), not only does PMD not cause any impairment, but it also provides a benefit of polarization diversity against polarization-dependent-loss-induced fading and consequently improves the system margin. The PMD benefit to fiber nonlinearity reduction in CO-OFDM systems is also predicted.**

*Index Terms*—**Coherent communications, optical fiber polarization, orthogonal frequency-division multiplexing (OFDM), polarization-mode dispersion (PMD).**

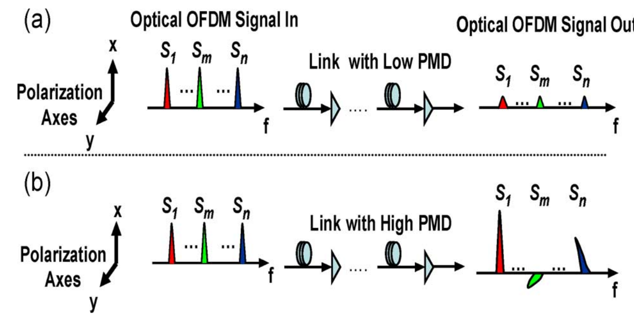


Fig. 1. Conceptual diagram of PDL-induced fading for a fiber link (a) with low PMD and (b) with high PMD. (a) Illustrates an example of PDL-induced deep fading where all the OFDM subcarriers suffer severe loss collectively.

## I. Introduction

POLARIZATION-MODE dispersion (PMD) and its compensation have attracted significant interest as the 40-Gb/s fiber-optic system has become a commercial reality and much higher transmission speed systems have been demonstrated. For conventional single-carrier systems, the impairment induced by a constant differential-group-delay (DGD) scales with the square of the bit rate, resulting in drastic PMD degradation for high-speed transmission systems [1]. Recently, we proposed a multicarrier modulation format called coherent optical orthogonal frequency-division multiplexing (CO-OFDM) to combat fiber dispersion [2]. We show that with CO-OFDM at 10 Gb/s, the PMD in the installed link causes practically no system penalty, and this PMD resilience holds true even at higher bit rates, in sharp contrast to the single-carrier counterpart [3]. Since PMD presents no practical detriment to a CO-OFDM system, the natural question to ask is: does PMD bring any benefit? Our detailed study in this letter reveals a similarity to the multipath interference paradox in RF communications in terms of the problems presented and the solutions provided. We show that despite the fact that PMD causes a severe detriment to conventional single-carrier systems, it provides a benefit of polarization diversity to multicarrier systems against polarization-dependent-loss (PDL)-induced fading, and therefore, may significantly improve the system performance. In particular, we find that with a 40-Gb/s CO-OFDM system, the PDL-induced penalty is reduced to 2.4 dB from 4.4 dB at an outage probability of $10^{-3}$, if a mean PMD of 150 ps is introduced. The PMD benefit to fiber nonlinearity reduction in CO-OFDM systems is also predicted. Furthermore, the core signal processing elements for implementing CO-OFDM, i.e., digital-to-analog converter (DAC) and analog-to-digital converter (ADC) have been commercially realized at 20 Gsample/s, and Moore's law predicts that the capability of the signal processing chips (DAC/ADC) increases approximately 70% per year [4], from the combination of improvement of chip switching speed and increase of the number of devices on the chip that facilitates large-scale parallel processing. Therefore, the semiconductor technological trend reveals that the signal processing power needed for CO-OFDM could keep up with the advancement of the optical transmission speed if not outpace it.

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## II. Principle of Polarization Diversity in a CO-OFDM System

OFDM is a special form of multicarrier modulation where a single data stream is transmitted over a number of lower rate orthogonal subcarriers [5]. It has been extensively investigated as a means of combating RF microwave multipath fading, and has been widely implemented in various digital communication standards such as wireless local area network standards (WiFi IEEE 802.11 a) [5]. In the time domain, an OFDM signal consists of a continuous stream of OFDM symbols with a regular period $T_s$, each containing an observation period $t_s$ and a guard interval $\Delta_G$. A CO-OFDM system consists of an electrical OFDM transmitter, an OFDM RF-to-optical up converter, an optical link, an OFDM optical-to-RF down converter, and an electrical OFDM receiver [2].

Fig. 1 shows the principle of the polarization diversity provided by PMD against PDL-induced fading. When a CO-OFDM signal passes through a fiber link, the amplified-spontaneous-emission (ASE) noise is added in each span. There are also numerous PDL elementss (PDLEs) along the path including optical amplifiers and various passive components. There is always some finite chance or outage probability that the OFDM signal experiences a large power loss along the path. When such an outage occurs, the output optical signal-to-noise ratio (OSNR) is severely degraded [6]. A sufficient system margin ought to be allocated for this PDL-induced degradation. Fig. 1(a) shows that, for a link without PMD, when the CO-OFDM signal traverses the link, the polarizations for all the OFDM subcarriers are aligned, and therefore, all the subcarriers likely experience the same loss, e.g., all the subcarriers may go to deep PDL fading at the same time. As a result, the signal is susceptible to PDL-induced fading for a link with no PMD. In contrast, Fig. 1(b) shows that for a link with high PMD, the polarizations of the OFDM subcarriers evolve differently while traversing the link. Therefore, the probability for all the subcarriers to simultaneously experience the severe loss is greatly reduced. At the output of the link, the power levels for the subcarriers as well as associated OSNRs are diversified. Therefore, PMD provides the benefit of polarization diversity against PDL-induced deep fading and subsequently improves the system performance. We note that incoherent optical OFDM (IO-OFDM) has also shown to provide a similar large chromatic dispersion (CD) tolerance [7]. The major difference between IO-OFDM and CO-OFDM is the receiver architecture because with IO-OFDM, a main optical carrier is sent along with the OFDM subcarriers and subsequently can be detected directly. However, IO-OFDM lacks polarization diversity against PDL-induced fading to the main optical carrier. Therefore, unlike with CO-OFDM, PMD does not provide much benefit to IO-OFDM.

## III. Simulation Model and Results

We first describe the receiver signal processing involved in the simulation. Following the same procedure as in [2] and assuming the channel spacing $\Delta f$ is sufficiently narrow by selecting large observation period $t_s$, the channel model for OFDM signals can be shown given by

$$\widetilde{C}'_{ki} = e^{j\phi_i} \cdot e^{j\Phi_D(f_k)} \cdot T(f_k) \cdot \widetilde{C}_{ki} + \widetilde{n}_{ki} \quad (1)$$

$$T(f_k) = \prod_{i=1}^{N} \exp\left\{\left(-\frac{1}{2}i \cdot \vec{\beta}_i \cdot f_k - \frac{1}{2}\vec{\alpha}_i\right) \cdot \vec{\sigma}\right\} \quad (2)$$

$$\Phi_D(k) = \pi \cdot c \cdot D_t \cdot f_k^2 / f_{LD1}^2 \quad (3)$$

where $\widetilde{C}'_{ki} = (c_x'^{ki}\ c_y'^{ki})^t$ is the received information symbol in the form of the Jones vector for the $k$th subcarrier in the $i$th OFDM symbol, $\widetilde{C}_{ki}$ is the corresponding transmitted information symbol, $\widetilde{n}_{ki} = (n_x^{ki}\ n_y^{ki})^t$ is the ASE noise including two polarization components, $f_k$ is the OFDM frequency for the $k$th subcarrier, $T(f_k)$ is the Jones matrix for the fiber link, $N$ is the number of the PMD/PDL cascading elements represented by their birefringence vector $\vec{\beta}_i$ and PDL vector $\vec{\alpha}_i$ [8], $\vec{\sigma}$ is the Pauli matrix vector, $\Phi_D(f_k)$ is the phase dispersion owing to the fiber CD [2], and $\phi_i$ is the OFDM symbol phase noise owing to the phase noises from the lasers and RF local oscillators at both the transmitter and receiver [2]. $\phi_i$ is usually dominated by the laser phase noise. We assume that $\Phi_D$ and $T(f_k)$ are constant within the time frame of signal processing equal to 100 OFDM frames (0.64 $\mu$s) in this letter. This tracking speed is sufficient for polarization change from any environmental or manual disturbance, and CD change in the fiber as well as in the electrical components within the transmitter and receiver from temperature variation or aging. In order to construct the constellation for each subcarrier and make symbol decision properly, the phase noise $\phi_i$ needs to be estimated for each OFDM symbol and removed from (1). The phase noise can be estimated by averaging over all the subcarriers given by

$$\phi_i = \left\langle 0.5 \cdot \mathrm{mod}\left(2 * \arg\left(c_y'^{ki}\right), 2\pi\right)\right\rangle \quad (4)$$

where $c_y'^{ki}$ is the one of the two polarization components of the received Jones vector $\widetilde{C}'_{ki}$ that has larger amplitude. Substituting (4) into (1), after simple manipulation, we have

$$\widetilde{C}^p_{ki} = e^{j\Phi_D(f_k)} \cdot T(f_k) \cdot \widetilde{C}_{ki} + \widetilde{n}^p_{ki} \quad (5)$$

where $\widetilde{C}^p_{ki} = \widetilde{C}'_{ki} \cdot e^{-j\phi_i}$, and $\widetilde{n}^p_{ki} = \widetilde{n}'_{ki} \cdot e^{-j\phi_i}$, which are the Jones vectors for the received symbol and noise after the symbol phase correction, respectively.

The expectation values for the received phase-corrected information symbols $\widetilde{C}^p_{ki}$ are obtained by averaging over a running window of 100 OFDM symbols. The expectation values for symbols "0" and "1" are computed separately by using received symbols $\widetilde{C}^p_{ki}$ for symbol "0" and "1", respectively. An error occurs when the transmitted "1" symbol in particular subcarrier is closer to the expected "0" at the receiver, or vice versa.

We carry out Monte Carlo simulations to verify the PMD benefit to CO-OFDM, with an OFDM symbol period of 6.4 ns, a guard interval of 710 ps, 64 (256) subcarriers for 10- (40) Gb/s systems, which gives the same subcarrier spacing for 10 and 40 Gb/s. BPSK encoding is used for each subcarrier. 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 ASE noise from the optical amplifiers is assumed to be white Gaussian noise and phase noise of the lasers is modelled as white frequency noise characterized by their linewidth. A total number of 200 OFDM symbols are used for each bit-error-rate (BER) simulation. The BER is computed by averaging over all the subcarriers and all the OFDM symbols. Each BER is converted to a $Q$ value accordingly.

The link is modelled as 16-span fibers each consisting of three high-birefringence (HIBI) fibers and one PDLE. The DGD and PDL of the polarization elements are chosen to give the total composite PMD/PDL value for the link. Each HIBI/PDLE is preceded by a polarization rotator (PR). The ASE noise is introduced into each span. The amount of ASE noise is adjusted to the level so that a nominal OSNR (with an ASE noise bandwidth of 0.1 nm) of 3.5 dB (9.5 dB) is maintained at the output of the fiber link for a bit rate of 10 Gb/s (40 Gb/s). The nominal 3.5 dB (9.5 dB) of OSNR gives a BER of $10^{-3}$ for a bit rate of 10 Gb/s (40 Gb/s) if the PDL is turned-off in the link. The link polarization state evolves by changing the angles of each PR before HIBI/PDLE, and the system $Q$ is recorded at each link polarization state. The $Q$ penalty is defined as the system $Q$ degradation from $Q$ of 9.8 dB corresponding to a BER of $10^{-3}$. The outage probability is defined as the probability that the system exceeds a specific $Q$ penalty.

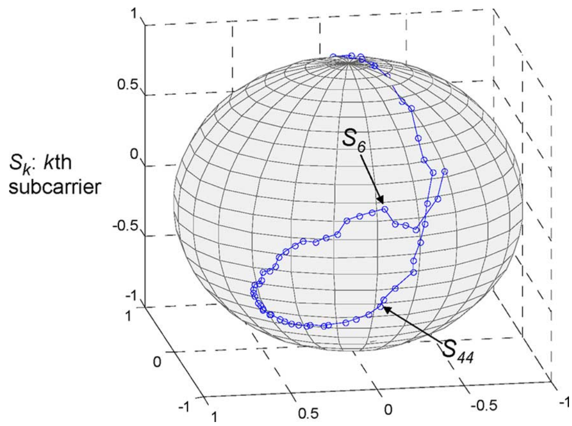


Fig. 2. Typical diagram of polarization evolution trajectory (PET) for 64 subcarriers within one OFDM symbol in 10-Gb/s OFDM systems. The link PMD state is one of the PMD realizations with a mean PMD of 150 ps.

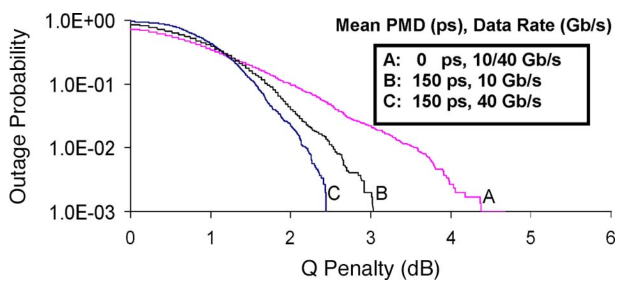


Fig. 3. Outage probability as a function of $Q$ penalty. The mean PDL in the system is 5 dB.

Fig. 2 shows a typical distribution of the Stokes vectors for the received symbols of 64 subcarriers within one OFDM symbol. It is equivalent to the polarization evolution trajectory (PET) when the OFDM frequency $f_k$ moves from the first subcarrier to the last subcarrier. It can be seen that owing to the high PMD, the polarization is widely dispersed across the Poincare sphere, which would have caused severe impairment to a single-carrier system such as a nonreturn-to-zero-based system. However, with CO-OFDM, the symbol decision is on the subcarrier basis, and subsequently PMD has negligible impairment on each subcarrier. Moreover, thanks to this very large polarization evolution across the entire OFDM spectrum, the collective PDL deep fading is avoided.

Fig. 3 shows the outage probability as a function of the $Q$ penalty. A mean PDL of 5 dB is assumed for all the simulations. We can see that without PMD in the system, there is a system $Q$ penalty of 4.4 dB at the outage probability of $10^{-3}$. However, if we introduce a mean PMD of 150 ps into otherwise the same system, to maintain the same outage probability of $10^{-3}$, the system penalty is reduced to 3.0 dB for a 10-Gb/s system, which is 1.4-dB improvement over the case of no PMD in the fiber link. A higher bit rate system at 40 Gb/s further reduces the $Q$ penalty to 2.4 dB with a PMD of 150 ps, a 2-dB improvement over the case of no PMD. This further improvement is attributed to a higher degree of diversity with a larger number of subcarriers for a higher bit rate system. We can see that the PMD in the fiber improves the system margin for PDL-induced penalty, and the improvement is enhanced for a higher bit rate system. We also note that a relatively large PMD is needed in the order of 150 ps to gain the benefit, which usually is not available in the fiber link. One of the possibilities is to artificially introduce high PMD into the fiber or optical components. Mitigation of a large PDL in CO-OFDM systems may significantly loosen the PDL specification for various components and subsequently bring appreciable cost saving. Finally, the fiber nonlinearity including self-phase modulation and cross-phase modulation will be reduced in PMD-supported CO-OFDM systems as previously reported for single-carrier systems [9]. Equivalently, the interchannel and intrachannel OFDM subcarrier four-wave mixing can be greatly reduced by phase/polarization mismatch between subcarriers in the presence of a large PMD. The detailed analysis of the PMD benefit to fiber nonlinearity reduction in CO-OFDM systems will be made known in future submission.

## IV. Conclusion

In contrast to conventional single-carrier systems where PMD is detrimental, with CO-OFDM, PMD provides a benefit of polarization diversity against PDL-induced fading and consequently improves system margin.

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