

Joint compensation of CD and PMD in direct-detected OFDM transmission using polarization-time coding

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Abstract: We propose and demonstrate a polarization-time coding (PTC) method which can effectively compensate both the CD and first order PMD in direct-detected OFDM transmission. Compared with the previous methods, the proposed PTC not only alleviates the need for the complex dynamic polarization controller but also exhibits superior transparencies to both the OFDM format and transmission data rate. For the proposed PTC method, we have analytically derived the transmission model with CD and first order PMD, and theoretically prove the PTC indeed can jointly compensate both CD and PMD. The numerical results show that, with the PTC method, both the previously proposed gapped and interleaved OFDM formats behave virtually immune to both CD and PMD with a price of 3-dB OSNR penalty in back-to-back (BtB). Aimed to mitigate this BtB 3-dB penalty, further partial PTC approach is proposed for trading the PMD tolerance with the BtB OSNR sensitivity. The interleaved OFDM system is found to gain profits in terms of lower sensitivity with the partial coding.

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1. Introduction

Optical frequency division multiplexing (OFDM) has attracted lots of attentions due to its ability to compensate the linear impairments enabled by powerful electrical signal processing [1–10]. Within the topics of OFDM, the direct-detected approach (DD-OFDM) [4–10] requires a simpler hardware implementation and less electrical processing complexity, thus being an alternative candidate for mid- and long-haul transmission other than the coherent approach (CO-OFDM) [1–3].

Although the DD-OFDM can compensate for the majority of linear impairments throughout the link, the polarization mode dispersion (PMD), which poses a relative time delay between the signals on the two orthogonal polarizations, results in data power fading which diminishes the received electrical signal to noise ratio and induces significant power penalty [11]. To mitigate the PMD fading issue, a receiver-side polarization beam splitter (PBS) method which gains the polarization diversity has been proposed for PMD compensation [8]. However, that technique requires the input carrier's state of polarization (SOP) to be equally aligned to both principal axes of the PBS, and therefore requires an adaptive polarization controller (PC) to dynamically adjust the carrier's SOP which makes this technique still far from reality. Later a self-polarization diversity receiver which collects the data on both polarizations by rotating the carrier's SOP by 90 degree has been proposed as a full PMD compensator without the need for an adaptive PC [9]. Unfortunately, this method uses a colored fiber Bragg grating (FBG) to separate the carrier and data sideband which excludes its application on other spectrally efficient gap-less OFDM formats [6,7]. In addition, the central frequency and bandwidth of the FBG filter should be optimized according to the bandwidth of the data sideband, which would limit its flexibility for diverse data rate transmission. Recently, a polarization diverse receiver [12] has also been proposed to remove the PMD distortion with a working principle similar to [9]. However, it also requires the colored filters and would suffer the similar issues, discussed above, as [9]. Thus, a laudable goal for the PMD compensator would be to provide a colorless compensating approach which is not only insensitive to the input SOP but also transparent to both the data format and data bandwidth.

In [10] we have proposed and demonstrated a PMD-tolerable DD-OFDM transmission using the polarization-time coding (PTC) which makes the receiver colorless, insensitive to input SOP, and transparent to both data format and bandwidth. The PTC approach, which has its origin in the wireless space-time coding [13], has earlier been introduced to the coherent optical systems for realizing the polarization insensitive receiver with enhanced PMD tolerance [14,15]. However, in the regime of direct-detection systems, to the best of our knowledge, this PTC approach has still lacked extensive studies so far. Therefore, to explore its potential advantages in DD-OFDM, our previous report [10] has firstly focused on its

improved PMD tolerance and demonstrated preliminary simulation results for the PTC-based interleaved OFDM systems. In this paper, we revisit the PTC approach in DD-OFDM by offering the transmission models and describing the equalization method. We also theoretically prove that the PTC approach indeed can compensate both the CD and first order PMD effects. The numerical results for both the conventional gapped OFDM [4–6,8,9,16] and the interleaved OFDM systems [6] with PTC approach are given. A 4-QAM, 10-Gbps DD-OFDM system is found to have negligible OSNR penalty under conditions of CD = 8,000 ps/nm and instantaneous differential group delay (DGD) = 300 ps. Greater CD and DGD tolerable could still be achieved as long as the cyclic prefix (CP) is preserved longer than the pulse broadening. Depending on the PMD conditions, we further use the partial PTC approach with the aim to potentially mitigate the BtB 3-dB OSNR penalty while still sustains moderate PMD tolerance. The simulation results show that the interleaved OFDM can benefit from the partial PTC in terms of the lower OSNR sensitivity with different DGD values; while the partial PTC is found to hardly improve any performance for the gapped OFDM systems.

2. Operation principle

2.1 Polarization-time coding (PTC) approach

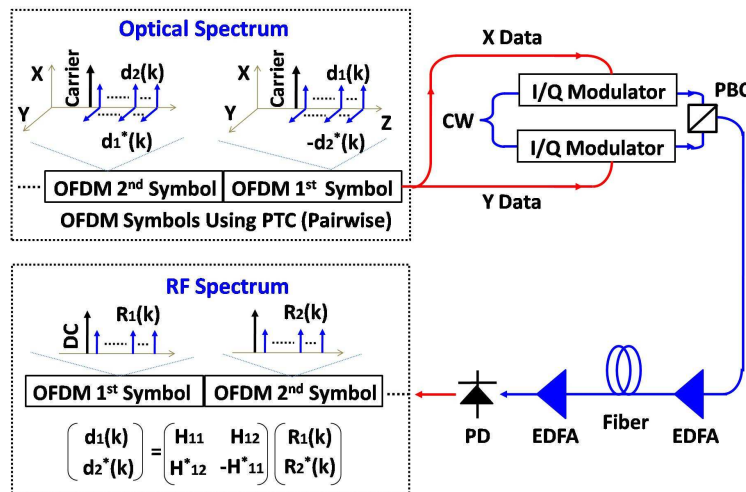


Fig. 1. Transmitter and receiver methods with the proposed Alamouti-type polarization-time coding (PTC) approach. CW: continuous wave, I/Q: inphase/quadrature, PBC: polarization beam combiner, EDFA: Erbium-doped fiber amplifier, PD: photodiode. RF: radio frequency.

Figure 1 schematically depicts the encoding and decoding methods, as well as the transmitter and receiver architectures, for a DD-OFDM transmission with the proposed PTC approach. In principle, PTC encodes the OFDM symbols pairwise in both the time and polarization domains. Here we demonstrate only one pair of data symbols, $d_1(k)$ and $d_2(k)$, on k th subcarrier, and the following OFDM symbols can be pairwise processed in a similar manner. The proposed PTC transmission can be described as: in x polarization, the carrier is employed and the 1st and 2nd OFDM symbol in the pair are modulated by $d_1(k)$ and $d_2(k)$, respectively; while in y polarization, the carrier is an option to be used and the 1st and 2nd OFDM symbols are encoded by $-d_2^*(k)$ and $d_1^*(k)$, respectively, as shown at the transmitter in Fig. 1. The superscript “*” stands for the complex conjugation. Note that the use of the y-polarization carrier is simply to control the output carrier’s SOP because via adjusting its amplitude and phase, with respect to those of x-polarization carrier, any SOP of the output carrier could be theoretically generated at the transmitter. Any possible benefit associated with the carrier’s SOP is still under investigated and, for simplicity, henceforth we consider only the x-polarization carrier in this paper. Since both polarizations are used for the data and the

encoded subcarriers, respectively, a higher-cost polarization-division-multiplexed (PDM) transmitter, as shown in Fig. 1, is required with this PTC approach.

After transmissions, as shown in Fig. 1, this OFDM signal with PTC can be directly detected via one simple photodiode. The post equalizer in the receiver also pairwise process the received symbols $R_1(k)$ and $R_2(k)$, which are the 1st and 2nd received symbols on k th subcarrier in the pair, to recover the transmitted symbols $d_1(k)$ and $d_2(k)$ by applying the inverse channel matrix as depicted at the bottom of the receiver block in Fig. 1. In practice, since the PMD is a time-varying random distortion, the training symbols should be periodically inserted in the OFDM packets in order to trace the PMD conditions in time. The frequency of training symbols in the OFDM packets should be set higher than the PMD varying rate.

To understand how the PTC approach can assist in compensating both the CD and PMD, an analytical model comprising the CD and PMD effects of the link is described as follows. We denote the carrier's complex amplitude in x-polarization as A and the electrical fields on both polarizations at the transmitter's output can be expressed by the 2X1 Jones matrix as:

$$T_1(t) = \begin{bmatrix} A + \sum d_1(k)e^{j2\pi f_k t} \\ -\sum d_2^*(k)e^{j2\pi f_k t} \end{bmatrix} \quad (1-a)$$

and

$$T_2(t) = \begin{bmatrix} A + \sum d_2(k)e^{j2\pi f_k t} \\ \sum d_1^*(k)e^{j2\pi f_k t} \end{bmatrix} \quad (1-b)$$

where T_1 and T_2 are the waveforms of the 1st and 2nd OFDM symbols, respectively, in the transmitted pair and f_k is the baseband frequency on k th subcarrier. Note that we have assumed the cyclic prefix (CP) is longer than the pulse broadening caused by CD and PMD, and thus we ignore the CP in the theoretical models throughout this paper. Here for the model we only consider the 1st order PMD effect, with which the fiber is assumed to be composed of two principal axes (i.e. the fast and slow axes) with different group velocities [9,17]. The optical power of the transmitted symbols would be partially coupled into the fast slow axes with an random angle of φ :

$$C_1(t) = \begin{bmatrix} \left(A + \sum d_1(k)e^{j2\pi f_k t} \right) \cos(\varphi) + \left(\sum d_2^*(k)e^{j2\pi f_k t} \right) \sin(\varphi) \\ \left(A + \sum d_1(k)e^{j2\pi f_k t} \right) \sin(\varphi) - \left(\sum d_2^*(k)e^{j2\pi f_k t} \right) \cos(\varphi) \end{bmatrix} \quad (2-a)$$

$$C_2(t) = \begin{bmatrix} \left(A + \sum d_2(k)e^{j2\pi f_k t} \right) \cos(\varphi) - \left(\sum d_1^*(k)e^{j2\pi f_k t} \right) \sin(\varphi) \\ \left(A + \sum d_2(k)e^{j2\pi f_k t} \right) \sin(\varphi) + \left(\sum d_1^*(k)e^{j2\pi f_k t} \right) \cos(\varphi) \end{bmatrix} \quad (2-b)$$

where C_1 and C_2 are the paired symbols coupled into the two principal axes of fiber with the upper element for the slow axis and the lower element for fast axis, respectively. After transmission, the CD and PMD phase evolution on the two polarizations will be involved into (2) and now have a form of

$$S_1(t) = \begin{bmatrix} \left(A + \sum d_1(k)e^{j2\pi f_k (t+Td/2) + j\theta_{cd}(k)} \right) \cos(\varphi) + \left(\sum d_2^*(k)e^{j2\pi f_k (t+Td/2) + j\theta_{cd}(k)} \right) \sin(\varphi) \\ \left(A + \sum d_1(k)e^{j2\pi f_k (t-Td/2) + j\theta_{cd}(k)} \right) \sin(\varphi) - \left(\sum d_2^*(k)e^{j2\pi f_k (t-Td/2) + j\theta_{cd}(k)} \right) \cos(\varphi) \end{bmatrix} \quad (3-a)$$

$$S_2(t) = \begin{bmatrix} \left(A + \sum d_2(k)e^{j2\pi f_k (t+Td/2) + j\theta_{cd}(k)} \right) \cos(\varphi) - \left(\sum d_1^*(k)e^{j2\pi f_k (t+Td/2) + j\theta_{cd}(k)} \right) \sin(\varphi) \\ \left(A + \sum d_2(k)e^{j2\pi f_k (t-Td/2) + j\theta_{cd}(k)} \right) \sin(\varphi) + \left(\sum d_1^*(k)e^{j2\pi f_k (t-Td/2) + j\theta_{cd}(k)} \right) \cos(\varphi) \end{bmatrix} \quad (3-b)$$

where T_d is the time delay between the slow and fast axes, and $\theta_{CD}(k)$ is the CD-induced phase evolution [6]. Ignoring the noise and filtering effect, after the square-law detection of photodiode, the converted electrical symbols can be represented as:

$$\begin{aligned} R_1(t) &= \left(A^* \sum d_1(k) \left[e^{j2\pi f_k (t+T_d/2) + j\theta_{CD}(k)} \cos^2(\varphi) + e^{j2\pi f_k (t-T_d/2) + j\theta_{CD}(k)} \sin^2(\varphi) \right] \right) \\ &+ \left(A^* \sum d_2^*(k) \left[e^{j2\pi f_k (t+T_d/2) + j\theta_{CD}(k)} - e^{j2\pi f_k (t-T_d/2) + j\theta_{CD}(k)} \right] \sin(\varphi) \cos(\varphi) \right) \end{aligned} \quad (4-a)$$

and

$$\begin{aligned} R_2(t) &= \left(A^* \sum d_2(k) \left[e^{j2\pi f_k (t+T_d/2) + j\theta_{CD}(k)} \cos^2(\varphi) + e^{j2\pi f_k (t-T_d/2) + j\theta_{CD}(k)} \sin^2(\varphi) \right] \right) \\ &+ \left(A^* \sum d_1^*(k) \left[-e^{j2\pi f_k (t+T_d/2) + j\theta_{CD}(k)} + e^{j2\pi f_k (t-T_d/2) + j\theta_{CD}(k)} \right] \sin(\varphi) \cos(\varphi) \right) \end{aligned} \quad (4-b)$$

After the discrete Fourier transform (DFT) processing, the extracted symbol on k th subcarrier can be expressed as:

$$R_1(k) = A^* \left\{ d_1(k) \left[e^{j\pi f_k T_d} \cos^2(\varphi) + e^{-j\pi f_k T_d} \sin^2(\varphi) \right] + d_2^*(k) \left[e^{j\pi f_k T_d} - e^{-j\pi f_k T_d} \right] \sin(\varphi) \cos(\varphi) \right\} e^{j\theta_{CD}(k)} \quad (5-a)$$

$$R_2^*(k) = A \left\{ d_2^*(k) \left[e^{-j\pi f_k T_d} \cos^2(\varphi) + e^{j\pi f_k T_d} \sin^2(\varphi) \right] + d_1(k) \left[-e^{-j\pi f_k T_d} + e^{j\pi f_k T_d} \right] \sin(\varphi) \cos(\varphi) \right\} e^{-j\theta_{CD}(k)} \quad (5-b)$$

By observing (5-a) and (5-b) we found that the received symbols $R_1(k)$ and $R_2(k)$ are functions of both the transmitted symbols $d_1(k)$ and $d_2(k)$. To decouple $d_1(k)$ and $d_2(k)$ from $R_1(k)$ and $R_2(k)$, we can express their relationships with a 2x2 matrix \mathbf{H} as:

$$\begin{bmatrix} R_1(k) \\ R_2^*(k) \end{bmatrix} = \mathbf{H} \begin{bmatrix} d_1(k) \\ d_2^*(k) \end{bmatrix} \quad (6)$$

where

$$\mathbf{H} = \begin{bmatrix} A^* \left[e^{j\pi f_k T_d} \cos^2(\varphi) + e^{-j\pi f_k T_d} \sin^2(\varphi) \right] e^{j\theta_{CD}(k)} & A^* \left[e^{j\pi f_k T_d} - e^{-j\pi f_k T_d} \right] \sin(\varphi) \cos(\varphi) e^{j\theta_{CD}(k)} \\ A \left[-e^{j\pi f_k T_d} + e^{-j\pi f_k T_d} \right] \sin(\varphi) \cos(\varphi) e^{-j\theta_{CD}(k)} & A \left[e^{-j\pi f_k T_d} \cos^2(\varphi) + e^{j\pi f_k T_d} \sin^2(\varphi) \right] e^{-j\theta_{CD}(k)} \end{bmatrix} \quad (7)$$

The channel matrix \mathbf{H} is found to be a function of the channel parameters, such as θ_{CD} , T_d , and φ . Then the transmitted symbols of $d_1(k)$ and $d_2(k)$ can be recovered by applying the inverse of the channel matrix \mathbf{H}^{-1} via

$$\begin{bmatrix} d_1(k) \\ d_2^*(k) \end{bmatrix} = \mathbf{H}^{-1} \begin{bmatrix} R_1(k) \\ R_2^*(k) \end{bmatrix} \quad (8)$$

Theoretically, (6) represents a typical two-variable linear equation in a matrix form and will have reasonable solutions if and only if the determinant of the channel matrix is non-zero. Moreover, since in reality the received symbols will also include the stochastic noises, a larger and a more stable determinant value of the channel matrix would better and more reliably discriminate the noise-corrupted paired transmitted symbols from each other when equalization. In other words, the receiving performance would vary with the channel CD and PMD conditions if the determinant of the channel matrix itself is a function of CD and PMD.

Thus, to ensure that the proposed PTC approach can fully compensate both the CD and PMD, we derive the channel matrix's determinant $Det(\underline{H})$ as follows,

$$Det(\underline{H}) = |A|^2 \left[\cos^4(\theta) + \sin^4(\theta) + 2\sin^2(\theta)\cos^2(\theta) \right] = |A|^2 \quad (9)$$

The channel determinant is shown to be equal to the carrier power $|A|^2 \neq 0$ and is independent of the CD and PMD parameters of θ_{CD} , T_d , and φ . Therefore, we conclude that the proposed PTC approach indeed can assist the OFDM signals to be virtually immune from both CD and 1st order PMD provided the CP is longer than the pulse broadening resulted from any distortion through the link. It is worth noting that, for deriving (8) and (9) we use no assumption for the data format and data rate (bandwidth), and thus it should theoretically work for diverse data rate and various proposed DD-OFDM formats [4,6,16].

2.2 Partial PTC approach

We have theoretically proved that the proposed PTC method can effectively enhance OFDM's

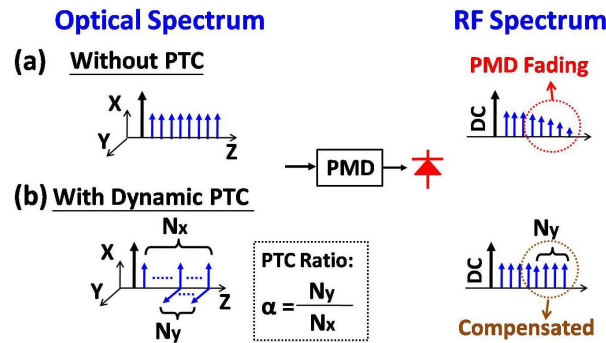


Fig. 2. (a) Without PTC approach the outer subcarriers, far from the optical carrier, will suffer severely the PMD fading. (b) The proposed partial PTC approach encodes only the outer subcarriers for protecting them from PMD. N_x : number of data subcarriers, N_y : number of protected (encoded) subcarriers.

immunities against CD and PMD. However, one obvious issue associated with the PTC approach is the introduction of the BtB 3-dB OSNR penalty resulting from the extra use of the encoded subcarriers in the y polarization, along which only redundant power is transmitted. In addition, the computation effort and related power consumptions for PTC approach are also greater than the conventional “uncoded” OFDM systems since with PTC approach all subcarriers need to be equalized with the more complex MIMO processing. It is worth noting that the referred “uncoded subcarriers” and the “uncoded systems” in the paper means those subcarriers and systems that are not with the PTC approach, which should be distinguished from those systems using the error correction codes. Through this paper we consider only the PTC coding but not any other type of error correction coding. In order to mitigate these negative side-effects brought by the PTC approach, we further propose the partial PTC approach which is specifically designed for combating the PMD. Since PMD has the most impact, which degrades the system performance in the form of power fading [12,17,18], on those subcarriers that are far from the optical carrier, it is possible to partially encode those vulnerable subcarriers, or those higher-indexed subcarriers, to reduce the extra OSNR penalty. The impact of PMD and the provided partial coding concept have been depicted in Fig. 2. The subcarriers for encoding will be selected from the outer-most ones who would suffer the most severe PMD fading [12,17,18]. To protect more subcarriers from the PMD fading, it is possible to further involve the inner subcarriers for encoding with a price of increased OSNR penalty. To quantify the coding extent with the partial PTC approach, the coding rate α is defined as:

$$\alpha = \frac{N_y}{N_x}$$

where N_x and N_y are the number of data subcarriers in x polarization and the number of encoded subcarriers in y polarization, respectively. It is worth noting that the specific case of $\alpha = 0$ corresponds to the conventional uncoded OFDM systems while $\alpha = 1$ matches the proposed PTC approach in the previous section. With the partial PTC approach, for the subcarriers from $k = (N_x - N_y + 1)$ to N_x , the transmitted symbols will be recovered via the MIMO processing (8); while for subcarriers from $k = 1$ to $(N_x - N_y + 1)$, the transmitted symbols can be recovered via the conventional one-tap equalizer [6]. Predictably, a higher coding rate will yield a better PMD tolerance but a worse sensitivity, and vice versa. Thus, there should theoretically be an optimum coding rate that trades the receiving sensitivity and the PMD tolerance. Besides, the computation efforts and power consumptions could be further reduced with the partial coding since only $\alpha N_x = N_y$ subcarriers are required to be equalized with MIMO processing while the other uncoded $(1 - \alpha)N_x$ subcarriers can be recovered via the simple one-tap equalizer.

For the partial PTC approach we also introduce the carrier to sideband power ratio (CSPR) with its definition as follows:

$$\text{CSPR} = \frac{|A|^2}{(1 + \alpha)N_x \langle |d_i|^2 \rangle}$$

where $\langle x \rangle$ represents the expectation value of x . Note that, in contrast to the previous definition [6], the sideband power in this formula is defined with the consideration of both the transmitted data in x polarization and the encoded redundancy in y polarization.

3. Numerical results and discussion

3.1 System parameters

In this section we will numerically demonstrate the capability of the proposed PTC approach in both the gapped OFDM (conventional OFDM) [4–6] and the interleaved OFDM [6] systems. The considered data format and assemble data rate are 4 QAM and 10 Gbps, respectively. The number of data subcarriers and total subcarriers (FFT size) are 48 and 256, resulting in an oversampling ratio of ~ 5.3 . The OFDM symbol duration is ~ 9.6 ns, which includes the desired OFDM symbol of 8.53 ns and the cyclic prefix (CP) of 1.07 ns. The fiber channel is modeled as linear and lossless with CD parameter of $D = 16$ ps/(nm.km). The 1st order PMD is also considered in the channel quantified with the differential group delay (DGD). Additive white Gaussian noise (AWGN), modeling the amplified spontaneous emission (ASE) noise, is loaded onto the system before receiving with a power spectral density (PSD) of N_o per polarization. The following optical filter, with 2nd-order Gaussian type, has a 3-dB bandwidth of ~ 15 GHz. The system performance is evaluated in terms of OSNR, which can be obtained with the consideration of both polarizations:

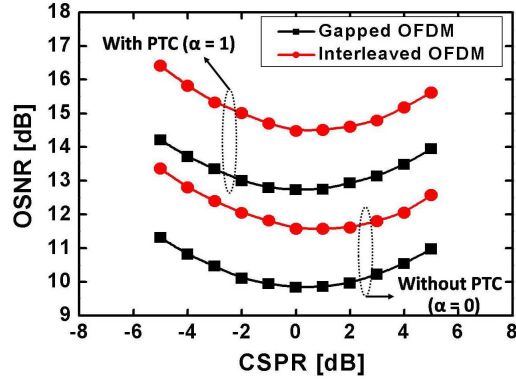


Fig. 3. OSNR vs. CSPR with and without PTC for the gapped- (typical) and interleaved-OFDM systems.

$$\text{OSNR} = \frac{(1 + \text{CSPR})}{\text{CSPR}} \frac{|A|^2}{(2N_o \times BW_o)}$$

in which BW_o is the noise bandwidth.

It is worth noting that, since the channel in simulations considers only the 1st PMD model, the instantaneous DGD, denoted in short as DGD, is mainly adopted for the presented results in this paper. However, the presented results can also be compared with those using the all-order PMD model [12,18], with which the mean DGD, $\langle \text{DGD} \rangle$, typically is applied, via the relationship of $\text{DGD} \approx 3.18 \langle \text{DGD} \rangle$ at an outage probability of 1×10^{-5} .

3.2 With PTC approach

In Fig. 3 we firstly investigate the optimum CSPR and the OSNR sensitivity for OFDM systems that use the PTC method. The received OSNR is defined with the noise bandwidth $BW_o = 12.5$ GHz (0.1 nm) throughout this paper. The optimum CSPR for both gapped and interleaved OFDM systems is found to be ~ 0 dB with and without the PTC approach. Without PTC approach, the optimum CSPR of 0 dB matches to the previous results [6] and the relevant discussions are omitted here. With PTC approach, in which the sideband power has been doubled by the encoded subcarriers, the carrier power also need be doubled to boost the electrical signal power against the enhanced beat noise introduced by the sideband on both polarizations. Due to the redundant sideband power and the enhanced carrier power, the systems with PTC would have an inevitable ~ 3 -dB power penalty compared with the systems without PTC. The OSNR difference, depending on the utilized filter bandwidth, of ~ 2 dB between the gapped and interleaved OFDM systems has been demonstrated and well explained in [17].

In Fig. 4 for gapped and interleaved OFDM systems we compare the CD and PMD tolerances with and without PTC approach. Without PTC the conventional one-tap equalizer has the inherent capability of de-rotating the CD-induced phase rotation and thus can protect the OFDM systems from suffering fiber CD, as can be seen in Fig. 4. However, when the PMD kicks in, the PMD fading will strongly attenuate the received signal's electrical SNR and result in a significant OSNR penalty. We found in Fig. 4 that there is an up to ~ 5 dB OSNR penalty when $\text{DGD} = 34$ and 38 ps for the gapped and interleaved systems, respectively. The better PMD tolerance of the interleaved OFDM system and the relevant discussions can be found in [12,17]. With the assistance of PTC, although there is an ~ 3 dB OSNR penalty in BtB, the systems exhibit much more robust tolerances against PMD whilst it can still retain the CD tolerance as well. In Fig. 4 we found even when the fiber length $L = 500$ km ($\text{CD} = 8,000$ ps/nm.km) and $\text{DGD} = 300$ ps, there is only negligible penalty found in systems with PTC.

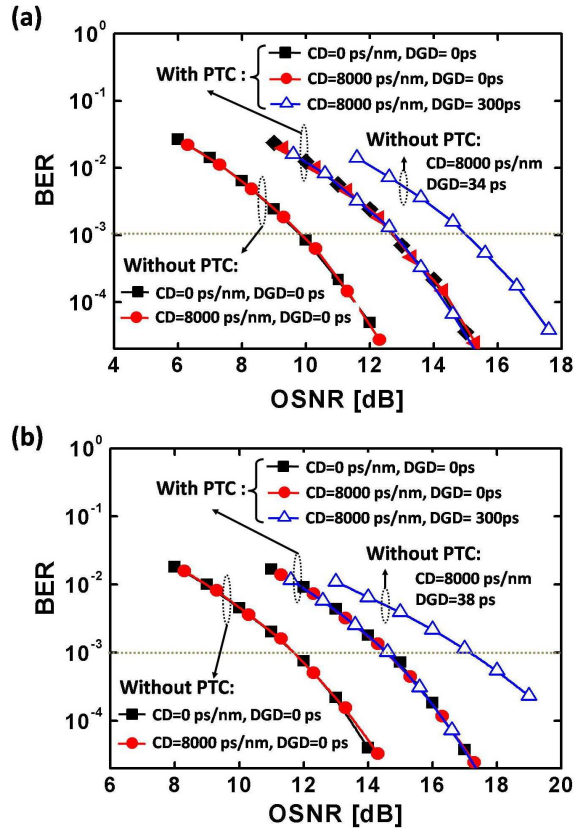


Fig. 4. BER vs. OSNR with and without PTC approach for the (a) gapped OFDM systems and the (b) interleaved OFDM systems. Note that the DGD shown here is the instantaneous value and it can be related to its mean value of $\langle \text{DGD} \rangle$ via $\text{DGD} \approx 3.18 \langle \text{DGD} \rangle$ at an outage probability = 10^{-5} ;

3.3 With partial PTC approach

In this section we use the partial PTC approach with the aim of leveraging the required OSNR and the PMD tolerance. Shown in Fig. 5 are the numerically obtained optimum CSPR and the corresponding OSNR at $\text{BER} = 10^{-3}$ with different PTC coding rate. The coding ratios of 0.25, 0.5, and 0.75 match to the encoded subcarrier numbers of 12, 24, and 36 over the total 48 data subcarriers. The optimum CSPR is found to be almost fixed and equal to 0 dB irrespective to the coding ratio. On the other hand, the OSNR sensitivity will go to a lower value with a decreased coding ratio with a price of sacrificed PMD tolerance. With the optimum CSPR values, the relative OSNR penalty resulted from PTC coding could be approximated by a simple formula of $10\text{Log}(1 + \alpha)$, matching the results presented in Fig. 5.

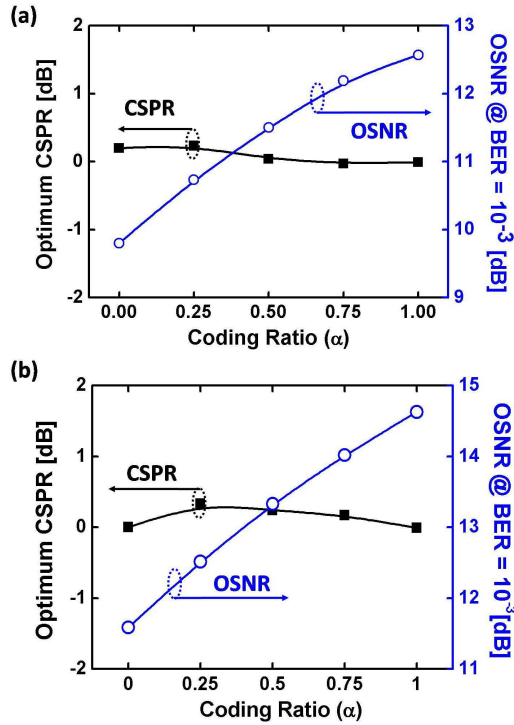


Fig. 5. Optimum CSPR and OSNR vs. the coding ratio for (a) gapped OFDM systems and (b) interleave OFDM systems.

The results of the PMD tolerances, in terms of DGD, with different coding ratio are depicted in Fig. 6. To focus on the PMD impact on the coding rate, we turn off the CD for obtaining the results in Fig. 6. The influences of partial PTC approach are found to be quite different between the gapped and interleaved systems. In the gapped systems, as shown in Fig. 6(a), the sensitivity is found to be lower-bounded by the curve with $\alpha = 0$ when $DGD < 28$ ps and by the curve with $\alpha = 1.0$ when $DGD \geq 28$ ps. Although the partial PTC approach with $\alpha = 0.25, 0.5$ and 0.75 can indeed provide the signal with enhanced PMD tolerance, it is found to outperform the uncoded systems ($\alpha = 0$) only when the $DGD \geq \sim 29$ ps at which the OSNR penalty > 3 dB is even worse than that introduced by the full PTC approach ($\alpha = 1$). Thus, for the gapped systems, either $\alpha = 0$ or $\alpha = 1$ would yield the optimum performance no matter what the PMD condition is. In other words, the partial PTC approach can hardly offer performance improvement in gapped OFDM systems. On the other hand, for the interleaved OFDM systems presented in Fig. 6(b), the OSNR sensitivity, depending on the amounts of DGD, is lower-bounded by the curves with different coding ratios. According to the expected PMD conditions, an appropriate coding ratio can be chosen and assigned to the transmitter for a better transmission performance. Therefore, in contrary to the gapped OFDM systems, the partial PTC approach can potentially enhance the PMD tolerance on the interleaved OFDM systems in receiving performance. The different impacts of the partial PTC approach on the gapped and interleaved systems could be attributed to the different subcarriers' spectral allocations. The partial PTC approach only encodes the outer subcarriers and leaves the inner subcarriers uncoded, as has been described in Section II. These uncoded subcarriers in gapped systems would still be vulnerable to PMD effect since the frequency spacing between the subcarriers and carrier, of which the larger gap width typically would have a worse PMD tolerance [9,17], is at least larger than the sideband bandwidth; whilst the uncoded subcarriers in interleaved systems would be relatively more robust to PMD since the uniformly

distributed subcarriers would make the uncoded subcarriers in average having a smaller frequency spacing from the optical carrier.

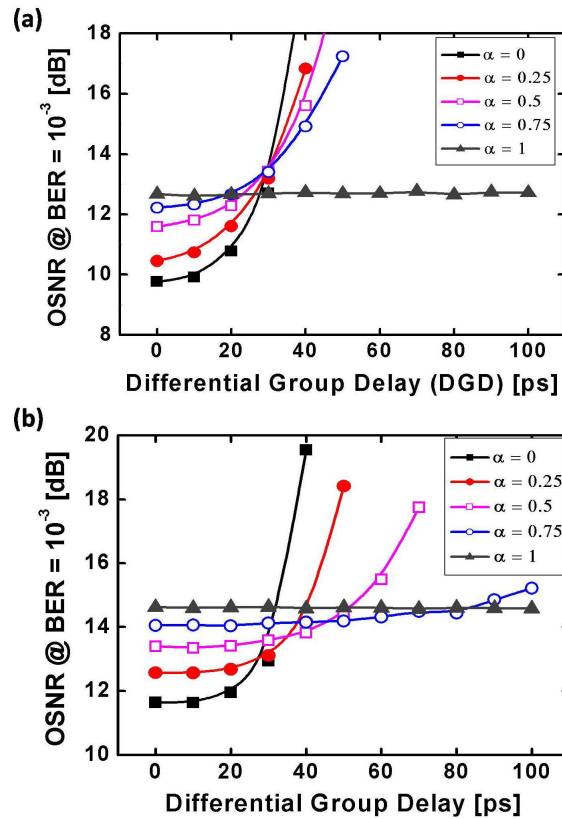


Fig. 6. OSNR sensitivities vs. differential group delay (DGD) for (a) gapped OFDM systems and (b) interleaved OFDM systems. Note that the DGD shown here is the instantaneous value and it can be related to its mean value of $\langle \text{DGD} \rangle$ via $\text{DGD} \approx 3.18 \langle \text{DGD} \rangle$ at an outage probability = 10^{-5} ;

4. Conclusions

We have proposed the PTC approach that provides the DD-OFDM signal immunities against both CD and PMD. With the PTC approach, the PMD power fading on both polarizations are complementary between the pair coded symbols and thus the symbols can be recovered at the receiver through adequate MIMO processing. We show by numerical results that, with the PTC approach, the 4-QAM, 10-Gbps DD-OFDM systems would have negligible OSNR penalty under the condition of experiencing 8,000-(ps/nm) CD and 300-ps DGD (≈ 94 -ps $\langle \text{DGD} \rangle$ at outage probability = 10^{-5}) at a price of extra 3-dB OSNR penalty. Aiming to further improve the sensitivity, we partially encode those subcarriers vulnerable to PMD attempting to balance the receiving sensitivity and the PMD tolerance. The simulation results show that for the gapped OFDM the partial PTC approach can hardly offer an effective means for achieving a lower OSNR sensitivity whilst the interleaved OFDM could be benefited, in terms of the lower OSNR sensitivity, by the partial PTC for different amounts of DGD. Since PMD is characterized as a stochastic process and has long been considered as an unsolved issue in direct detection systems, the PTC approach, proven to be a powerful means for completely removing PMD, would still have its uniqueness and would deserve future investigations for exploring any of its potential benefit.