Spectrum-Efficient Coherent Optical Zero Padding OFDM for Future High-Speed Transport Networks

Linglong Dai and Zhaocheng Wang
Tsinghua National Laboratory for Information Science and Technology,
Department of Electronic Engineering, Tsinghua University, Beijing 10084, China
E-mail: daill@tsinghua.edu.cn

Abstract—**By fully exploiting the optical channel properties, we propose in this paper the coherent optical zero padding orthogonal frequency division multiplexing (CO-ZP-OFDM) for future high-speed optical transport networks to increase the spectral efficiency and improve the system reliability. Unlike the periodically inserted training symbols in conventional optical OFDM systems, we design the polarization-time-frequency (PTF) coded pilots scattered within the time-frequency grid of the ZP-OFDM payload symbols to realize low-complexity multiple-input multiple-output (MIMO) channel estimation with high accuracy. Compared with conventional optical OFDM systems, CO-ZP-OFDM improves the spectral efficiency by about 6.62%. Simulation results indicate that the low-density parity-check (LDPC) coded bit error rate of the proposed scheme only suffers from no more than 0.3 dB optical signal-to-noise ratio (OSNR) loss compared with the ideal back-to-back case even when the optical channel impairments like chromatic dispersion (CD) and polarization mode dispersion (PMD) are severe.**

I. Introduction

Recently, initiated by the pioneering work of Shieh [1], coherent optical orthogonal frequency division multiplexing (CO-OFDM) has attracted considerable research interest as a promising candidate for future high-speed optical transport networks beyond 100 Gb/s [2], [3]. In addition, polarization division multiplexing (PDM) can be used jointly with CO-OFDM to double the system throughput without increasing the signal bandwidth [4].

One key feature of CO-OFDM is its superior tolerance to optical channel impairments including chromatic dispersion (CD), polarization mode dispersion (PMD), and polarization dependent loss (PDL) [3]. The optical channel could be presented essentially by a multiple-input multiple-output (MIMO) Jones matrix [1], [4], and the periodically inserted training symbols are usually used to estimate the channel so that channel equalization could be realized to compensate for the optical impairments with low complexity [3], [4]. The time-multiplexed single-polarization training symbols are proposed for channel estimation [4], [5], whose performance could be improved either by the time-domain averaging among multiple training symbols [4], [6], or by the intra-symbol frequency-domain averaging (ISFA) within the same training symbol [7]. A pair of correlated dual-polarization (CDP) training symbols are proposed to further improve the performance [8]. However, those solutions based on training symbols with all subcarriers used as pilots reduce the spectral efficiency [5], and the large interval between two adjacent training symbols lowers the channel tracking capability when PMD of the optical channel may vary relatively fast [2].

To fully exploit the optical channel properties to achieve high spectral efficiency and reliable performance, we propose in the paper the coherent optical zero padding OFDM (CO-ZP-OFDM) transmission scheme based on polarization-time-frequency (PTF) coded pilots for future high-speed optical transport networks. Unlike the periodically inserted training symbols where all active subcarrier are used as pilots, the PTF-coded pilots sparsely scattered within the time-frequency grid of the ZP-OFDM payload symbols are used to achieve the corresponding low-complexity PTF channel estimation with high accuracy. As a result, CO-ZP-OFDM improves the spectral efficiency by about 6.62%, and enjoys the coded bit error rate (BER) with no more than 0.3 dB optical signal-to-noise ratio (OSNR) penalty compared with the ideal back-to-back (B2B) case even when the optical channel impairments like CD and PMD are large.

The remainder of this paper is organized as follows. The proposed CO-ZP-OFDM system model is described in Section II. The corresponding CO-ZP-OFDM receiver design is presented in Section III. Section IV addresses the performance analysis of the proposed scheme. Numerical results are shown in Section V. Finally, conclusions are drawn in Section VI.

Notation: We use the upper and lower boldface letters to denote matrices and column vectors, respectively; $\mathbf{0}_{M\times N}$ denotes the $M \times N$ zero matrix; $\mathbf{F}_N$ denotes the normalized $N \times N$ fast Fourier transform (FFT) matrix whose $(n+1, k+1)$th entry being $\exp(-j2\pi nk/N)/\sqrt{N}$; $(\cdot)^*$, $(\cdot)^T$, and $(\cdot)^H$ denote the complex conjugate, transpose, and Hermitian transpose, respectively; $\widetilde{x}$ means that x is a frequency-domain signal; Finally, $\widehat{x}$ presents the estimate of x.

II. CO-ZP-OFDM System Model

In this section, the transmission frame structure of the proposed CO-ZP-OFDM scheme with PDM is addressed at first, then the signal model over optical channels is presented.

A. CO-ZP-OFDM Transmission Frame Structure

Fig. 1 compares the frame structure of the conventional CO-OFDM system with that of the proposed CO-ZP-OFDM scheme for high-speed optical transport networks. Normally, cyclic prefix (CP) is used as the guard interval in most CO-OFDM systems (we explicitly use the term "CO-CP-OFDM"

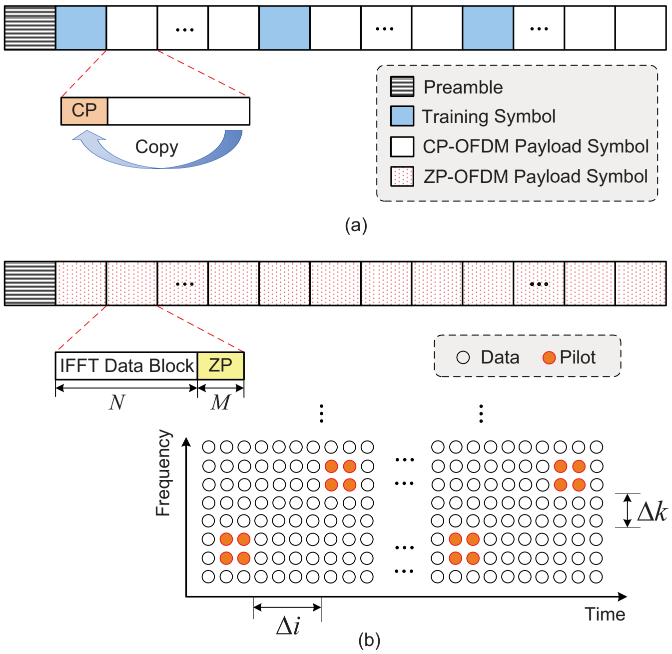

Fig. 1. Frame structure for optical OFDM block transmission: (a) Conventional CO-CP-OFDM; (b) Proposed CO-ZP-OFDM.

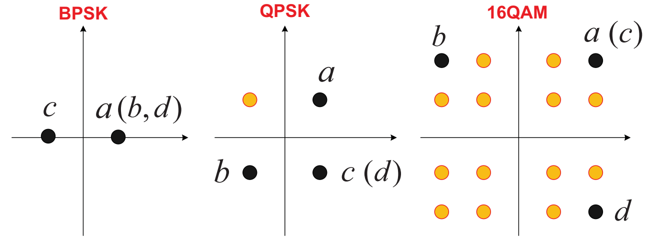

Fig. 2. Examples of the pilot pattern selection when BPSK, QPSK, and 16QAM constellations are used.

to stand for the conventional CO-OFDM schemes using CP as the guard interval in the rest part of the paper), and the training symbols with all active subcarriers used as pilots are periodically inserted for channel estimation.[1] On the contrary, without CP and training symbols, the proposed CO-ZP-OFDM transmission frame is composed of one preamble and the followed ZP-OFDM payload symbols, whereby ZP replaces CP as the guard interval [9], and the PTF-coded pilots sparsely scattered within the time-frequency grid of ZP-OFDM payload symbols are used for channel estimation.

In the time-domain, when PDM is used to double the system throughput, the ith ZP-OFDM symbol $\mathbf{z}_x^{(i)} = [z_{0,x}^{(i)}, z_{1,x}^{(i)}, \cdots, z_{N+M-1,x}^{(i)}]^T$ in the x-polarization consists of the inverse FFT (IFFT) data block $\mathbf{s}_x^{(i)} = [s_{0,x}^{(i)}, s_{1,x}^{(i)}, \cdots, s_{N-1,x}^{(i)}]^T$ of length N and the followed zero padding of length M, i.e.,

$$\mathbf{z}_x^{(i)} = \left[\left(\mathbf{s}_x^{(i)} \right)^T \mathbf{0}_{M\times 1}^T \right]^T, \tag{1}$$

where $\mathbf{s}_x^{(i)} = \mathbf{F}_N^H \widetilde{\mathbf{s}}_x^{(i)}$ is obtained by applying IFFT [10] to the frequency-domain data $\widetilde{\mathbf{s}}_x^{(i)} = [\widetilde{s}_{0,x}^{(i)}, \widetilde{s}_{1,x}^{(i)}, \cdots, \widetilde{s}_{N-1,x}^{(i)}]^T$, which may contian some useful constellation signals after low-density parity-check (LDPC) encoding [11] and some PTF-coded pilots. Similarly, the IFFT data block of the ith ZP-OFDM symbol in the y-polarization can be denoted by $\mathbf{s}_y^{(i)} = \mathbf{F}_N^H \widetilde{\mathbf{s}}_y^{(i)}$, where $\widetilde{\mathbf{s}}_y^{(i)}$ may also contains some PTF-coded pilots as $\widetilde{\mathbf{s}}_x^{(i)}$ in the x-polarization.

In the frequency domain, the PTF-coded pilots for the proposed CO-ZP-OFDM scheme can be explained from the following four aspects:

1) *Four-pilot cluster*. The pilots appear cluster by cluster, wherein each cluster is composed of four adjacent pilots in the time-frequency grid with the frequency-domain distance Δk and time-domain distance Δi. Since the optical channel usually has flat frequency response and slow time variation [12], Δk and Δi could be large, e.g., $\Delta k = 8$ and $\Delta i = 8$ can be used when $N = 2048$.
2) *Polarization-time orthogonal pilots*. In the polarization-time domain, the kth subcarriers in the ith and $(i+1)$th ZP-OFDM symbols in both x-polarization and y-polarization take the form

$$\begin{bmatrix} \widetilde{p}_{k,x}^{(i)} & \widetilde{p}_{k,x}^{(i+1)} \\ \widetilde{p}_{k,y}^{(i)} & \widetilde{p}_{k,y}^{(i+1)} \end{bmatrix} = \begin{bmatrix} a & c \\ b & d \end{bmatrix}, \tag{2}$$

where $\widetilde{p}_{k,x}^{(i)}$ denotes the pilot in the x-polarization on the subcarrier k in the ith ZP-OFDM symbol. The pilots in (2) can be selected from the standard constellations (e.g., BPSK, QPSK, 16QAM, etc.), and they should be orthogonal, i.e., $ac^* + bd^* = 0$. Fig. 2 examples the pilot cluster selection when BPSK, QPSK, and 16QAM constellations are used. For the simplest form when BPSK constellation is considered, $a = b = d = 1$ and $c = -1$ could be used without loss of generality.[2]
3) *Polarization-frequency orthogonal pilots*. In the polarization-frequency domain, for the specific ith ZP-OFDM symbol, the pilots on the kth and $(k+1)$th subcarriers in the x-polarization and y-polarization follow the form of

$$\begin{bmatrix} \widetilde{p}_{k,x}^{(i)} & \widetilde{p}_{k+1,x}^{(i)} \\ \widetilde{p}_{k,y}^{(i)} & \widetilde{p}_{k+1,y}^{(i)} \end{bmatrix} = \begin{bmatrix} a & c \\ b & d \end{bmatrix}, \tag{3}$$

where the pilots in each cluster are also orthogonal (i.e., $ac^* + bd^* = 0$), which can be achieved similarly to that in (2). Combining (2) and (3), we can find that the proposed pilot cluster has orthogonal pilots both in the polarization-time and polarization-frequency domains. That is just the reason why the term "PTF-coded pilots" is used in this paper.
4) *Pilot power boosting*. The average pilot power could be higher than the useful data power to enhance the channel estimation performance [11], [13]. More specifically,

[1] For example, a pair of training symbols are used after every 20 CP-OFDM symbols in [7].

[2] Note that other pilot selection schemes, such as $a = b = c = 1, d = -1$, could also be used.

compared with the useful data, the amplitude of the pilots could be boosted by a factor of β, which could be $\beta = \sqrt{2}$, $\beta = 2$, $\beta = 2\sqrt{2}$, etc.

B. Signal Model over Optical Channels

When the optical channel is time-invariant during one ZP-OFDM symbol, the received IFFT data block in ZP-OFDM is essentially the same as that in CP-OFDM after overlap-and-add (OLA) processing [9], whereby the "tail" caused by the multipath effect is added to the front part of the received IFFT data block. Then, the received frequency-domain signal $\widetilde{\mathbf{r}}_k^{(i)} = [\widetilde{r}_{k,x}^{(i)}\ \widetilde{r}_{k,y}^{(i)}]^T$ corresponding to the transmitted signal $\widetilde{\mathbf{s}}_k^{(i)} = [\widetilde{s}_{k,x}^{(i)}\ \widetilde{s}_{k,y}^{(i)}]^T$ on the kth subcarrier in the ith ZP-OFDM symbol can be presented by [4], [14]

$$\widetilde{\mathbf{r}}_k^{(i)} = \widetilde{\mathbf{H}}_k^{(i)} \widetilde{\mathbf{s}}_k^{(i)} + \widetilde{\mathbf{w}}_k^{(i)}, \tag{4}$$

where

$$\widetilde{\mathbf{H}}_k^{(i)} = \begin{bmatrix} h_{k,xx}^{(i)} & h_{k,xy}^{(i)} \\ h_{k,yx}^{(i)} & h_{k,yy}^{(i)} \end{bmatrix} \tag{5}$$

is the 2×2 MIMO Jones channel matrix including the optical impairment effects like CD, PMD, and PDL [14], and $\widetilde{\mathbf{w}}_k^{(i)}$ denotes the additive white Gussian noise (AWGN) dominated by the amplified spontaneous emission (ASE) [4]. It is clear from (4) that channel estimation is essential for optical impairments compensation.

III. CO-ZP-OFDM Receiver Design

After timing and frequency synchronization using the preamble [13], [15], the OLA method is adopted to reconstruct the cyclicity of the received IFFT data block within the ZP-OFDM symbol [9]. Then, the PTF-coded pilots can be extracted from the frequency-domain IFFT data block to realize the following polarization-time-frequency channel estimation.

A. Polarization-Time Channel Estimation

Since the optical fiber channel is varying slowly, $\widetilde{\mathbf{H}}_k^{(i)} = \widetilde{\mathbf{H}}_k^{(i+1)}$ could be assumed. Then, based on the polarization-time orthogonal pilots (2) and the signal model (4), the received pilots $\left[\widetilde{d}_{k,x}^{(i)}\ \widetilde{d}_{k,x}^{(i+1)}\right]^T$ in the x-polarization and $\left[\widetilde{d}_{k,y}^{(i)}\ \widetilde{d}_{k,y}^{(i+1)}\right]^T$ in the y-polarization can be rewritten as

$$\begin{bmatrix} \widetilde{d}_{k,x}^{(i)} \\ \widetilde{d}_{k,x}^{(i+1)} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} h_{k,xx}^{(i)} \\ h_{k,xy}^{(i)} \end{bmatrix} + \begin{bmatrix} \widetilde{w}_{k,x}^{(i)} \\ \widetilde{w}_{k,x}^{(i+1)} \end{bmatrix}, \tag{6}$$

$$\begin{bmatrix} \widetilde{d}_{k,y}^{(i)} \\ \widetilde{d}_{k,y}^{(i+1)} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} h_{k,yx}^{(i)} \\ h_{k,yy}^{(i)} \end{bmatrix} + \begin{bmatrix} \widetilde{w}_{k,y}^{(i)} \\ \widetilde{w}_{k,y}^{(i+1)} \end{bmatrix}. \tag{7}$$

When the simple pilot pattern $a = b = d = 1, c = -1$ is used, the polarization-time channel estimation can be achieved by

$$\begin{cases} \widehat{h}_{k,xx}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,x}^{(i)} - \widetilde{d}_{k,x}^{(i+1)}\right) = h_{k,xx}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,x}^{(i)} - \widetilde{w}_{k,x}^{(i+1)}\right), \\ \widehat{h}_{k,xy}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,x}^{(i)} + \widetilde{d}_{k,x}^{(i+1)}\right) = h_{k,xy}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,x}^{(i)} + \widetilde{w}_{k,x}^{(i+1)}\right), \\ \widehat{h}_{k,yx}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,y}^{(i)} - \widetilde{d}_{k,y}^{(i+1)}\right) = h_{k,yx}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,y}^{(i)} - \widetilde{w}_{k,y}^{(i+1)}\right), \\ \widehat{h}_{k,yy}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,y}^{(i)} + \widetilde{d}_{k,y}^{(i+1)}\right) = h_{k,yy}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,y}^{(i)} + \widetilde{w}_{k,y}^{(i+1)}\right). \end{cases} \tag{8}$$

It is clear from (8) that the noise has been averaged, i.e., the noise variance is halved and the equivalent OSNR for channel estimation is increased by 3 dB, so diversity gain can be achieved by the polarization-time channel estimation.

B. Polarization-Frequency Channel Estimation

Based on the fact that optical fiber channel usually has relatively flat channel frequency response (CFR), $\widetilde{\mathbf{H}}_k^{(i)} = \widetilde{\mathbf{H}}_{k+1}^{(i)}$ could be assumed. Then, using the polarization-frequency orthogonal pilots (3) and the signal model (4), the received pilots $\left[\widetilde{d}_{k,x}^{(i)}\ \widetilde{d}_{k+1,x}^{(i)}\right]^T$ in the x-polarization and $\left[\widetilde{d}_{k,y}^{(i)}\ \widetilde{d}_{k+1,y}^{(i)}\right]^T$ in the y-polarization during the ith ZP-OFDM symbol can be rewritten as

$$\begin{bmatrix} \widetilde{d}_{k,x}^{(i)} \\ \widetilde{d}_{k+1,x}^{(i)} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} h_{k,xx}^{(i)} \\ h_{k,xy}^{(i)} \end{bmatrix} + \begin{bmatrix} \widetilde{w}_{k,x}^{(i)} \\ \widetilde{w}_{k+1,x}^{(i)} \end{bmatrix}, \tag{9}$$

$$\begin{bmatrix} \widetilde{d}_{k,y}^{(i)} \\ \widetilde{d}_{k+1,y}^{(i)} \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} h_{k,yx}^{(i)} \\ h_{k,yy}^{(i)} \end{bmatrix} + \begin{bmatrix} \widetilde{w}_{k,y}^{(i)} \\ \widetilde{w}_{k+1,y}^{(i)} \end{bmatrix}. \tag{10}$$

When the pilot pattern $a = b = d = 1, c = -1$ is used, the polarization-frequency channel estimation can be achieved by

$$\begin{cases} \widehat{h}_{k,xx}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,x}^{(i)} - \widetilde{d}_{k+1,x}^{(i)}\right) = h_{k,xx}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,x}^{(i)} - \widetilde{w}_{k+1,x}^{(i)}\right), \\ \widehat{h}_{k,xy}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,x}^{(i)} + \widetilde{d}_{k+1,x}^{(i)}\right) = h_{k,xy}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,x}^{(i)} + \widetilde{w}_{k+1,x}^{(i)}\right), \\ \widehat{h}_{k,yx}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,y}^{(i)} - \widetilde{d}_{k+1,y}^{(i)}\right) = h_{k,yx}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,y}^{(i)} - \widetilde{w}_{k+1,y}^{(i)}\right), \\ \widehat{h}_{k,yy}^{(i)} = \frac{1}{2}\left(\widetilde{d}_{k,y}^{(i)} + \widetilde{d}_{k+1,y}^{(i)}\right) = h_{k,yy}^{(i)} + \frac{1}{2}\left(\widetilde{w}_{k,y}^{(i)} + \widetilde{w}_{k+1,y}^{(i)}\right). \end{cases} \tag{11}$$

Similar to the polarization-time channel estimation, the polarization-frequency channel estimation could also achieve the diversity gain of 3 dB since (11) indicates that the noise variance has been halved.

Based on the fact that the optical channel has relatively flat CFR and slow time-varying properties, the obtained CFR over the PTF-coded pilots according to (8) or (11) can be used to acquire the CFR over the data subcarriers via low-complexity linear interpolation either in the time or frequency domain or both [16]. Then, optical channel impairments compensation can be realized by channel equalization, and the LDPC decoding is used to output the final detected information bits.

IV. Performance Analysis

A. Spectral Efficiency

Both the training symbols in CO-CP-OFDM and the PTF-codeed pilots in CO-ZP-OFDM would reduce the spectral efficiency. For the proposed CO-ZP-OFDM scheme, the pilot occupation ratio η is

$$\eta = \frac{4 \times 3}{(2 \times 3 + \Delta i \times 2) \times (2 \times 3 + \Delta k \times 2)} \times 100\%. \tag{12}$$

Table I compares the pilot occupation ratio between a typical CO-CP-OFDM system [7] and the proposed CO-ZP-OFDM scheme when $N = 2048, M = 256$ are used for both schemes. In CO-CP-OFDM, a pair of training symbols are inserted after every 20 CP-OFDM payload symbols [7] for channel tracking, so the pilot occupation ratio is 9.10%. For the proposed CO-ZP-OFDM scheme, the PTF-coded pilots with the frequency-domain distance $\Delta k = 8$ and time-domain distance $\Delta i = 8$ are sufficient to track the channel variation, so the pilot occupation ratio is only 2.48%. Therefore, CO-ZP-OFDM has higher spectral efficiency than CO-CP-OFDM by about 6.62%.

TABLE I
COMPARISON OF PILOT OCCUPATION RATIO.

Transmission Scheme	Pilot Occupation Ratio
Conventional CO-CP-OFDM [7]	9.10%
Proposed CO-ZP-OFDM	2.48%

B. Equivalent OSNR Variation

Compared with CO-CP-OFDM, ZP in CO-ZP-OFDM has the zero power, leading to the increased equivalent OSNR of

$$\Delta\mathrm{OSNR}_1 = 10\log_{10}\left(\frac{M+N}{N}\right). \quad (13)$$

So the equivalent OSNR gain of 0.51 dB will be achieved by using ZP as the guard interval when $M = N/8$.

On the other hand, the pilot power boosting would reduce the equivalent OSNR at the optical receiver by

$$\Delta\mathrm{OSNR}_2 = 10\log_{10}\left(\eta\beta^2 + (1-\eta)\right), \quad (14)$$

where the useful data power is normalized to 1. Table II lists the OSNR loss when different pilot power levels are used, which indicates that the channel estimation performance in CO-ZP-OFDM could be substantially improved by pilot power boosting without obvious OSNR loss.

TABLE II
COMPARISON OF OSNR LOSS DUE TO PILOT POWER BOOSTING.

β	OSNR loss for CO-CP-OFDM	OSNR loss for CO-ZP-OFDM
$\sqrt{2}$	0.38 dB	0.11 dB
2	1.05 dB	0.31 dB
$2\sqrt{2}$	2.15 dB	0.70 dB

C. Computational Complexity

When the PTF-coded pilots are simply selected from the BPSK constellation, both the polarization-time channel estimation (8) and the polarization-frequency channel estimation (11) can be realized by simple add/subtraction operations. Therefore, the PTF channel estimation has very low complexity. Note that the CO-CP-OFDM systems [4], [8], [15] also have low-complexity channel estimation. The OLA algorithm [9] only requires one add operation to remove the "tail" caused by the multipath effect to the front part of the received IFFT data block, so its complexity is also low. In summary, CO-ZP-OFDM and CO-CP-OFDM have similar yet low computational complexity.

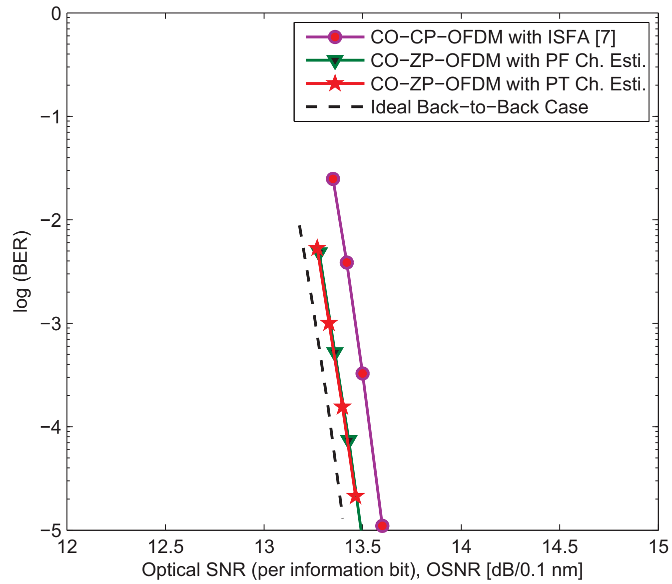

Fig. 3. Coded BER performance comparison with the CD of 2,000 ps/nm and ⟨DGD⟩ of 100 ps.

V. NUMERICAL RESULTS

We provide the numerical results in this section to evaluate the performance of the proposed CO-ZP-OFDM transmission scheme based on PTF-coded pilots for future high-speed optical transport networks. The simulation setup is similar to the PDM OFDM system in [5]. The bandwidth of the OFDM signal is about 35.4 GHz. The IFFT length is 2048, the ZP length is 256, which corresponds to the guard interval duration of about 4.5 ns. The optical CD of 2,000 ps/nm and 8,000 ps/nm are considered. The PMD with the mean differential group delay (denoted by ⟨DGD⟩) of 100 ps and 400 ps are evaluated. The amplitude factor used to boost the pilot power is set as $\beta = 2$. The constellation scheme 16QAM is adopted. We choose the LDPC code in [17] due to its low complexity and very low error floor resulted from the absence of 4-cycles in its graph [18]. The sum-product algorithm (SPA) is adopted for iterative soft-decision decoding with the iteration number of 50 [18]. The polarization-diversity optical hybrid detector has the optical local oscillator with the line bandwidth of 100 kHz. The OSNR at the receiver is defined with the 0.1 nm noise bandwidth.

Fig. 3 shows the coded bit error rate (BER) performance of the proposed CO-ZP-OFDM scheme with the CD of 2,000 ps/nm and ⟨DGD⟩ of 100 ps. For comparison, we also present the BER performance of the conventional CO-CP-OFDM system with reliable performance [7], where the ISFA method implements the frequency-domain averaging among several neighboring subcarriers in the same training symbol could achieve similar reliable performance as the time-domain averaging scheme requiring much more training symbols. The BER in the ideal B2B case where the channel has no distortion but with optical noise, is used as the comparison benchmark. The small CD indicates that the optical channel in each ZP-OFDM symbol does not fluctuate much in the frequency domain, and

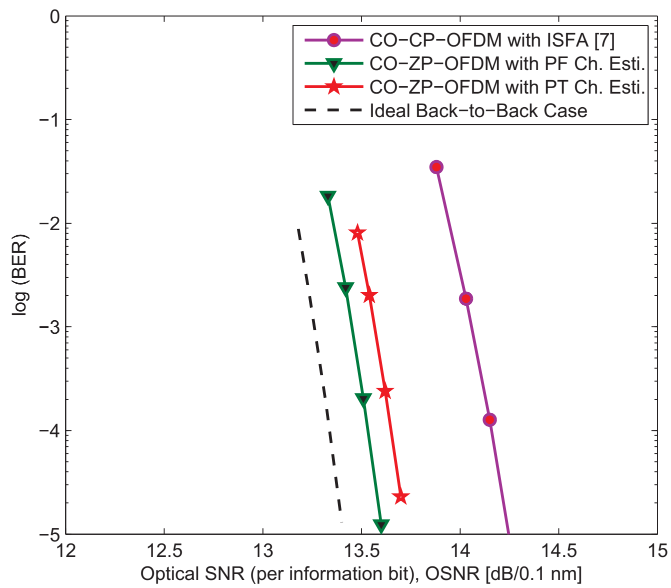

Fig. 4. Coded BER performance comparison with the CD of 8,000 ps/nm and ⟨DGD⟩ of 400 ps.

the relatively small ⟨DGD⟩ means that the channel is varying slowly in the time domain. We can observe from Fig. 3 that the conventional CO-CP-OFDM system and the proposed CO-ZP-OFDM scheme have similar BER performance in this case. For CO-ZP-OFDM, the polarization-time channel estimation (denoted by "PT Ch. Esti.") has very close performance to that of the polarization-frequency channel estimation (denoted by "PF Ch. Esti."). They both perform slightly better than CO-CP-OFDM with the OSNR gain of 0.1 dB, and enjoy less than 0.1 dB OSNR penalty with respect to the B2B case. In Fig. 4 when CD increases to 8,000 ps/nm and ⟨DGD⟩ is as large as 400 ps, both polarization-frequency channel estimation and polarization-time channel estimation in CO-ZP-OFDM perform much better than their counterpart in CO-CP-OFDM, and only suffer from no more than 0.3 dB OSNR penalty compared with the ideal B2B case.

VI. Conclusions

In this paper, the CO-ZP-OFDM transmission scheme based on PTF-coded pilots is proposed for future high-speed optical transport networks, whereby the optical channel properties are fully exploited to achieve high spectral efficiency and reliable performance. The PTF-coded pilots enable low-complexity PTF channel estimation with high performance due to the obtained diversity gain and pilot power boosting. The proposed CO-ZP-OFDM scheme has higher spectral efficiency than conventional CO-CP-OFDM systems, and the reliable performance under severe CD and PMD conditions has also been demonstrated. In addition, the proposed scheme can be easily extended to other CO-CP-OFDM systems to achieve higher spectral efficiency and enhanced performance.

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