A Side Information Free PTS-PAPR Reduction in Coherent Optical OFDM Systems Using Superimposed Training

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Abstract— In this paper, we report a side information free partial transmit sequence (PTS) technique to reduce the peak-to-average power ratio (PAPR) for coherent optical OFDM systems using superimposed training. Simulation results show that this scheme can reduce PAPR effectively, and have a slight BER performance improvement compared with the conventional superimposed training coherent optical OFDM systems.

1. INTRODUCTION

Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) [1] is a promising technology for optical long-haul systems because of its high spectral efficiency, high flexibility and its nature combination with digital signal processing (DSP). However, there is a common belief that OFDM has inferior tolerance to fiber nonlinearities because of its high peak-to-average-power ratio (PAPR). Therefore, several PAPR reduction techniques have been proposed [2–5] to reduce this nonlinear impairment. Among these methods, one promising scheme is the partial transmit sequence (PTS) [2, 6]. In traditional PTS schemes (T-PTS) [7], input data symbols are divided into disjointed sub-blocks which are separately phase-rotated by individually selected phase factors during PAPR optimization process. In order to detect the data symbols properly at the receiver, the phase factors are also transmitted as side information (SI) when data symbols are sent, resulting in a loss of data rate.

In this paper, an efficient SI free PTS-PAPR reduction scheme is presented, which combines the channel estimation and T-PTS method to reduce the PAPR of OFDM signals, called as the ST-PTS method. Its key idea is that the side information of PTS is considered as a part of channel frequency response which can be estimated within each interleaved PTS sub-block based on superimposed training (ST). Thus,the original OFDM signals could be directly recovered via superimposed training channel estimation [8] without any knowledge of the SI at the receiver. Furthermore, to enhance the performance of BER, a side information recovery is performed across the interleaved ST-PTS sub-blocks at receiver to achieve an accurate channel estimation over the whole sub-blocks. Simulation results demonstrate that the proposed method can reduce PAPR effectively and have slightly BER performance improvement compared with the conventional superimposed training coherent optical OFDM systems.

2. TRADITIONAL PTS SCHEME

For an OFDM system with N subcarriers, the transmitted signal in the time domain is given by

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) e^{j2\pi kn/N}, \quad 0 \le n < N \tag{1}$$

where $X = [X(0), X(1), \ldots, X(N-1)]$ is the input data block with N independent modulated data symbols $X(k)(0 \le k \le N-1)$. In general, the PAPR of the OFDM signal $x(n)$ is defined as

$$PAPR = \frac{\max\limits_{0 \le n \le N-1} |x(n)|^2}{E\left[|x(n)|^2\right]} \tag{2}$$

where $E[\cdot]$ represents the expectation.

In T-PTS schemes [2], the input data vector X is firstly partitioned into M disjointed sub-blocks $(N = MG)$, which are represented by the vectors $\{X^{(m)}, m = 0, 1, \ldots, M-1\}$. Therefore, we can get

$$X = \sum_{m=0}^{M-1} X^{(m)}, \quad 0 \le m \le M-1 \tag{3}$$

where $X^{(m)} = [X_0^{(m)}, X_1^{(m)}, \ldots, X_{G-1}^{(m)}]$ is the mth sub-block. Then each sub-block is rotated by a phase factor set $b_m = e^{j\phi_m}$, i.e., $X^{(m)} \cdot b_m$. In general, the phase factor set is limited with a finite number of elements to reduce the complexity. In this paper, we chose $\phi \in \{0, \pi\}$, this means $b_m \in \{\pm 1\}$. Taking Inverse Fast Fourier Transform of $X^{(m)} \cdot b_m$, we obtain $x^{(m)} = \left[x_0^{(m)}, x_1^{(m)}, \ldots, x_{G-1}^{(m)}\right], 0 \leq m \leq M-1$. The sub-blocks are combined to find the optimal set of b_m with respect to minimize the PAPR of the transmitted OFDM signals. At the receiver, for the T-PTS method, when no bits are reserved to protect SI, the SI should be sent to the receiver with $(M-1)\log_2 Q$ bits, where Q is the number of the allowed phase factors, resulting in a decrease in the data rate.

3. ST BASED SI FREE PTS SCHEME

In ST based method [8], after the complex training sequence is superimposed to the complex data in frequency domain, the resulted signal is given by:

$$X_k = S_k + P_k \tag{4}$$

where S_k and P_k denote the complex data symbols and the pilot sequence respectively, $k = 0, 1, \ldots, N-1$ is the sub-carrier index, and N is the number of sub-carriers. The data symbols S_k is assumed to have a zero mean. The interleaved T-PTS algorithm [2] is then followed to reduce the PAPR of OFDM signal according to the system model described above. Therefore, we can get the OFDM signal equipped with a phase factor b_m, i.e.,

$$X = \sum_{m=0}^{M-1} X^{(m)} = \sum_{m=0}^{M-1} b_m X_k, \quad k = Mg + m \tag{5}$$

where M is the number of sub-blocks, m is the sub-block index, and $g = 0, 1, \ldots, G-1$ is the element-index of the sub-blocks.

The optical fiber channel is assumed to have a discrete-time channel impulse response (CIR), i.e., $h = [h_0, h_1, \ldots, h_{L-1}]$, where L is the channel length. The corresponding channel frequency response (CFR) is $H = [H_0, H_1, \ldots, H_{N-1}]$.

3.1. Joint Channel and Phase Factor Estimation: Initial Estimation

At the receiver, after taking the DFT operation, the received signal in the frequency domain can be written as

$$Y_k = X_k H_k + W_k, \quad 0 \leq k \leq N-1 \tag{6}$$

where H_k is the channel frequency response (CFR), and W_k is the frequency domain additive white Gaussian noise with zero mean. Using the PTS, the received signal Y_k is partitioned into M interleaved sub-blocks $Y_g^{(m)}$ $(0 \leq g \leq G-1,\ N = MG)$, where the type of the disjoint sub-blocks is the same as that of the transmitter. As a result, the mth sub-block is

$$Y_g^{(m)} = b_m X^{(m)} H^{(m)} + W^{(m)} \tag{7}$$

where $X^{(m)} = X_k,\ k = Mg + m$ and $H^{(m)} = H_k,\ k = Mg + m$ denote the data and CFR of the mth sub-block, respectively.

Denote

$$\hat{H}^{(m)} = b_m H^{(m)} \tag{8}$$

as the virtual frequency channel response, which is the combination of the traditional channel frequency response and the phase rotation factors used in the PTS method.

Substituting Eq. (4) and Eq. (8) into Eq. (7), we have

$$\begin{aligned} E\left(Y^{(m)}\right) &= E\left(X^{(m)}\hat{H}^{(m)} + W^{(m)}\right) = E\left(S^{(m)}\hat{H}^{(m)} + P^{(m)}\hat{H}^{(m)} + W^{(m)}\right) \\ &= E\left(S^{(m)}\hat{H}^{(m)}\right) + E\left(P^{(m)}\hat{H}^{(m)}\right) + E\left(W^{(m)}\right) \end{aligned} \tag{9}$$

where $S^{(m)}$ and $P^{(m)}$ denote the complex data symbols and the pilot sequence of the mth sub-block respectively. In Eq. (9), the first and third expectations are zero since $S^{(m)}$ and $W^{(m)}$ are zero mean, and clearly, the second expectation operator can be removed to give

$$E\left(Y^{(m)}\right) = P^{(m)}\hat{H}^{(m)} \tag{10}$$

Therefore, we have CFR of the mth sub-block, i.e.,

$$\hat{H}^{(m)} = E\left(Y^{(m)}\right)/P^{(m)} \tag{11}$$

Hence, data symbols within each interleaved sub-block can be directly recovered without SI by

$$\hat{X}^{(m)} = Y^{(m)}/\hat{H}^{(m)} - P^{(m)} \tag{12}$$

3.2. Estimation Enhancement: Phase Equalization Across Sub-blocks

Generally, the performance of PTS-PAPR reduction is directly proportional to the number of sub-blocks M. However, for a given ST power, a large M results in worse BER performance since the channel is estimated within each sub-block. To enable an efficient PAPR reduction without degrading the BER performance, an improved channel estimation with phase equalization across disjoint PTS sub-blocks can be adopted [6].

Note that, typically, in a CO-OFDM system, CFR H_k can be considered as time-invariant within the whole sub-blocks. The Phase factor set used at the transmitter can be recovered as follows.

$$\hat{b}_m = \frac{b_m H^{(m)}}{b_1 H^{(1)}} = \frac{\hat{H}^{(m)}}{\hat{H}^{(1)}}, \quad 0 \le m \le M-1 \tag{13}$$

where m is the sub-block index and b_m is the phase factor of the mth sub-block. After the decision of $\hat{b}_m$, the phase difference of the ST aided data sequence of each PTS sub-block is compensated by $\hat{Y}^{(m)} = Y^{(m)}/\hat{b}_m$. Hence, the estimation of CFR can be re-performed over the whole sub-blocksas

$$H_k = E(Y_k)/P_k, \quad 0 \le k \le N-1 \tag{14}$$

where $Y_k = \sum_{m=0}^{M-1} \hat{Y}^{(m)}$ is the ST aided data sequence with no phase difference. Finally, data symbols over the whole sub-blocks can be recovered using Eq. (12). To further improve the performance of channel estimation and thus yields a better BER performance, a decision feedback method [8, 9] can be adopted at receiver, where the recovered data symbols based on the channel estimation of the previous iteration by Eq. (12) are combined with the ST symbols to obtain a better channel estimate. After only a few iterations, the quality of the detected data symbols is substantially improved. For more details may refer to the ST based method [8, 9].

4. ST-PTS CO-OFDM SYSTEM ARCHITECTURE

The block diagram of ST-PTS CO-OFDM system is shown in Fig. 1. At the CO-OFDM transmitter, apseudo random binary sequence (PRBS)is firstly modulated by using 4-QAM. After serial to parallel conversion, periodic training sequences are arithmetically added on to the data streams in frequency domain.To minimize the PAPR of the ST aided data streams, the T-PTS scheme is performed for each OFDM symbol. Next, IDFT and cyclic prefix (CP) insertion are followed to generate the time-domain OFDM signal which is then parallel/serial converted and D/A converted by two DACs operating at a sample rate of 32 GHz with 5-bit resolution. Finally, the optical domain OFDM signal generated via external modulation MZM is transmitted to the fiber link which consist of multiple spans of standard single mode fiber (SSMF), and each span have 80-km of the fiber with a span loss of 16 dB, an EDFA with a noise figure of 6 dB, and a 50-GHz optical band-pass filter.

At the CO-OFDM receiver, coherent detection with polarization diversity receiver is used for signal reception. After converting the signal from optical to electrical domain by using photo-detectors,the electrical signal is firstly resampled to 2 samples/sample and the resolution of the ADC is assumed to be 5 bits. To constrain the residual channel memory length to the one that can be detected by a training sequence with a short period, CD is compensated using a frequency domain equalizer [10], which is not shown in Fig. 1. After serial to parallel conversion, sub-block channel estimation is performed based on ST channel estimation method using Eq. (11). The phase

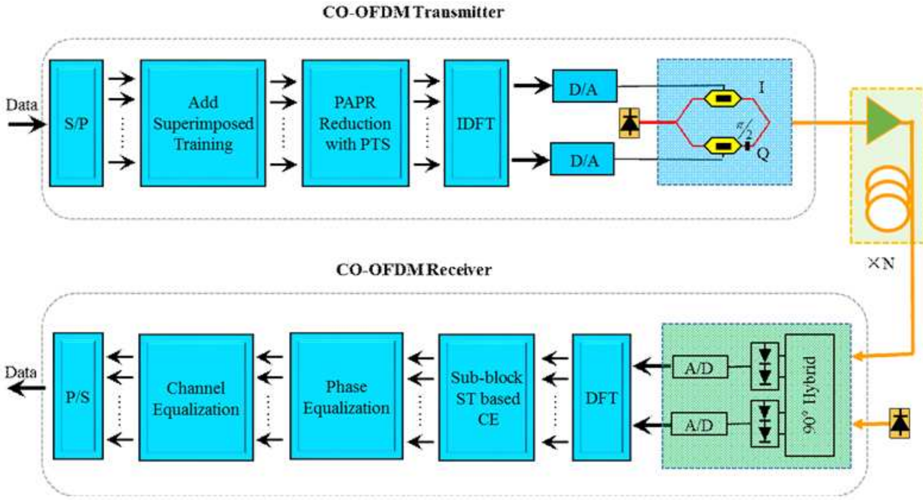

Figure 1: Simulation setup of the ST-PTS CO-OFDM system.

factor estimation is then carried out with the decision of the result of Eq. (13). Next, an accurate channel estimation is achieved over the whole sub-blocks on the condition that the phase difference of the ST aided data sequence of each PTS sub-block is equalized. Finally, the inverse of the estimated channel frequency response is applied to the received signal for the frequency domain equalization.

5. SIMULATION RESULTS AND DISCUSSION

The performance of the ST-PTS based SI free PAPR reduction scheme is evaluated through simulation on a coherent optical OFDM transmission system with the comparison of the traditional ST based channel estimation scheme. For each run, 16 OFDM symbols are used, each with 4096 point IFFT ($N_{\text{IFFT}} = 4096$) and oversampling ratio is 4 in all the simulations.Meanwhile, QPSK is used for mapping. The signal-to-pilot power ratio of the superimposed training is set to 12 dB. For simplicity, the set of phase rotation factors is $b_m \in \{1, -1\}$ and the number of the sub-blocks is 4 or 8.

Figure 2(a) shows the measured complementary cumulative distribution function (CCDF) curves of the PAPR in ST-PTS-OFDM, ST-OFDM and conventional OFDM (Conv-OFDM) transmission systems, respectively. As seen from Fig. 2(a), the PAPR performance of ST-OFDM scheme is very close to that of the conventional OFDM scheme. Compared with ST-OFDM method, the ST-PTS-OFDM offers about 1.7 dB and 2.8 dB of the PAPR reduction at $CCDF = 10^{-2}$ when $M = 4$ and $M = 8$, respectively.

Figure 2(b) shows the back-to-back (B2B) performance of the ST-PTS-OFDM and ST-OFDM methods when $M = 8$, respectively. For both schemes, one iteration feedback is used. It can be seen

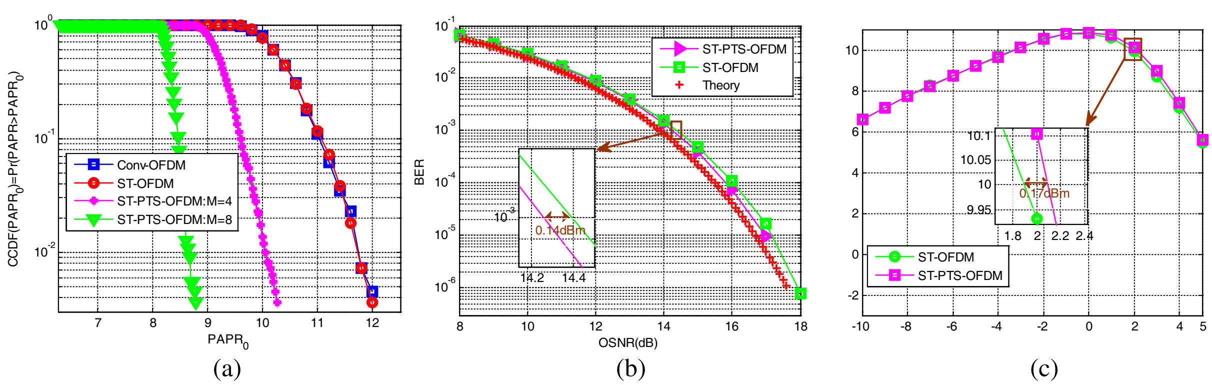

Figure 2: (a) CCDF comparison between the ST-PTS and ST methods, (b) back-to-back performances with different OSNR values, (c) comparison of 1600 km fiber performance.

that the BER performance of the ST-PTS-OFDM method is better than that of the ST-OFDM scheme with about 0.14 dB improvement at BER = 1E-3.

We also considered the nonlinear tolerance of the ST-PTS-OFDM approach after fiber transmission, which is shown in Fig. 2(c). A transmission link of 20 spans of SSMF is used. And the CD coefficient is 16 ps/ns/km while the fiber nonlinear refractive index is 2.6e-20 m^2/W. An Erbium-doped fiber amplifier (EDFA) with a noise Figure $NF = 6$ dB is placed at the end of each fiber span. The results show that at Q-factor = 10, about 0.17 dBm launch-power penalty is achieved compared with the traditional ST based optical OFDM system. Therefore, the ST-PTS-OFDM method enables PAPR reduction of the traditional OFDM scheme based on [8, 11], and has a slight BER performance improvement.

6. CONCLUSION

The concept of the ST based SI free PTS-PAPR reduction for coherent optical OFDM transmission systems was introduced. The side information of PTS is considered as a part of channel frequency response which can be estimated using ST based channel estimation. With the aid of ST, an accurate channel estimation can be obtained followed by phase equalization across each interleaved PTS sub-block. Compared with the traditional ST-OFDM scheme without PAPR reduction, ST-PTS-OFDM method can get an OSNR improvement about 0.15 dB in both B2B and 1600 km fiber link coherent optical transmission systems.

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REFERENCES

1. Shieh, W. and C. Athaudage, "Coherent optical orthogonal frequency division multiplexing," *Electron. Lett.*, Vol. 42, No. 10, 587–589, 2006.
2. Le Khoa, D., N. Tu, N. Thu, and N. Phuong, "Scramble PAPR reduction algorithms for fiber nonlinearity mitigation in long haul coherent optical OFDM systems," *IJCST. Org*, Vol. 3, No. 12, 8–13, 2012.
3. Tang, Y., W. Shieh, and B. S. Krongold, "DFT-spread OFDM for fiber nonlinearity mitigation," *IEEE Photonics Technol. Lett.*, Vol. 22, No. 16, 1250–1252, Aug. 2010.
4. Han, S. and J. Lee, "PAPR reduction of OFDM signals using a reduced complexity PTS technique," *IEEE Signal Process. Lett.*, Vol. 7, 2733–2740, Apr. 2004.
5. Liang, X., W. Li, W. Ma, and K. Wang, "A simple peak-to-average power ratio reduction scheme for all optical orthogonal frequency division multiplexing systems with intensity modulation and direct detection," *Opt. Express*, Vol. 17, No. 18, 15614–15622, Aug. 2009.
6. Tan, G., Z. Li, J. Su, and H. Zhang, "Superimposed training for PTS-PAPR reduction in OFDM: A side information free data recovery scheme," *Commun. Netw.*, 2013.
7. Jiang, T. and Y. Wu, "An overview: Peak-to-average power ratio reduction techniques for OFDM signals," *IEEE Trans. Broadcast.*, Vol. 54, No. 2, 257–268, Jun. 2008.
8. Guo, C., Z. Han, and L. Huang, "Channel estimation using superimposed training for coherent optical OFDM systems," *Asia Commun. Photonics Conf. 2013*, No. 3, AF2F.77, 2013.
9. Orozco-Lugo, A. G., M. M. Lara, and D. C. McLernon, "Channel estimation using implicit training," *IEEE Trans. Signal Process.*, Vol. 52, No. 1, 240–254, Jan. 2004.
10. Kudo, R., T. Kobayashi, K. Ishihara, Y. Takatori, A. Sano, and Y. Miyamoto, "Coherent optical single carrier transmission using overlap frequency domain equalization for long-haul optical systems," *J. Light. Technol.*, Vol. 27, 2009.
11. Huang, Z., J. Li, S. Zhang, F. Zhang, and Z. Chen, "Investigations of SPM suppression by PAPR reduction in coherent optical OFDM systems," *Asia Commun. Photonics Conf. Exhib.*, ThO5, 2009.