Hybrid Interleaved-PTS Scheme for PAPR Reduction in OFDM Systems

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Abstract. As one of the main shortcomings in orthogonal frequency division multiplexing (OFDM) systems, large peak-to-average power ratio (PAPR) induces system performance degradation. To improve this problem, partial transmit sequence (PTS) is one of the most promising PAPR reduction schemes, but it requires a complicated phase weighting process which results in large computational complexity. In this paper, a hybrid interleaved-PTS PAPR reduction scheme in OFDM systems is proposed. In proposed hybrid interleaved-PTS scheme, alternate optimization and block interleaving are employed for reducing computational complexity and improving PAPR reduction performance respectively. With the extensive computer simulations and analysis, the proposed hybrid interleaved-PTS scheme can achieve dramatic reduction in computational complexity and similar PAPR reduction performance compared with conventional PTS (C-PTS).

Keywords: OFDM · PAPR reduction · PTS · Interleaving · Computational complexity

1 Introduction

As an attractive multicarrier modulation, orthogonal frequency division multiplexing (OFDM) meets the demand of high data rate [1] and has been adopted in many fields of wireless communications [2]. However, OFDM systems suffer from system performance degradation because of its high OFDM signal peaks which is usually described by peak-to-average power ratio (PAPR).

Recently, for the sake of improving PAPR performance of OFDM systems, some PAPR reduction schemes have been presented [3,4], such as precoding [5], companding [6], clipping and filtering [7,8], adaptive all-pass filters [9], selected mapping [10,11], partial transmit sequence [12,13], constellation shaping [14] and so on. Partial transmit sequence (PTS) falls into one category and can be viewed as the linear PAPR reduction scheme with good PAPR property. However, in order to find the optimal OFDM candidate sequence, a complicated phase weighting process for all the subblock sequences must be introduced. To alleviate the computational complexity problem of conventional PTS (C-PTS),

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some extensions of PTS have been presented. In [13], an alternate optimized PTS (AO-PTS) is given for reducing computational complexity. Different from C-PTS, only half of the subblock sequences in AO-PTS are involved in the phase weighting process. By doing this, though the reduction in computational complexity can be obtained, the loss of PAPR reduction performance cannot be avoided due to the fact that the number of generated candidate sequences is decreased compared with C-PTS.

In this paper, a hybrid interleaved-PTS PAPR reduction scheme for OFDM systems is proposed. In proposed hybrid interleaved-PTS scheme, alternate optimization and block interleaving are incorporated, where the use of alternate optimization can achieve significant reduction in computational complexity and the interleaving for the first subblock sequence is employed for improving PAPR reduction performance. After the extensive computer simulations are done, the proposed hybrid interleaved-PTS scheme can achieve dramatic reduction in computational complexity and similar PAPR reduction performance compared with C-PTS.

The rest of this paper is organized as follows. In Sect. 2, the corresponding background is described, including the OFDM system model, the definition of PAPR and the measurement of PAPR reduction performance. Section 3 gives conventional PTS scheme for PAPR reduction in OFDM systems. Section 4 introduces proposed hybrid interleaved-PTS scheme and its computational complexity is discussed. In Sect. 5, massive computer simulation results and the corresponding performance analysis are given. In the end, a brief conclusion is done in Sect. 6.

2 Background

The input bit stream is firstly mapped by M-ary phase shift keying (M-PSK) or M-ary quadrature amplitude modulation (M-QAM). Then, the obtained complex symbols are combined into a sequence $\boldsymbol{X} = [X_0, X_1, \cdots, X_{N-1}]$ and the OFDM signal can be obtained by transmitting this sequence into an OFDM system with N subcarriers.

For the discrete-time OFDM signal, the nth sample x_n can be described by

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N}, 0 \leq n \leq N-1 \tag{1}$$

where X_k denotes complex symbol carried by the kth subcarrier and $j = \sqrt{-1}$.

In OFDM systems, PAPR is defined by the ratio of the peak power to the average power of an OFDM signal, given by

$$\text{PAPR}(\boldsymbol{x}) = 10\log_{10} \frac{\underset{0 \leq n \leq N-1}{max} \{|x_n|^2\}}{E\{|\boldsymbol{x}|^2\}} \text{dB} \tag{2}$$

where $max\{\cdot\}$ and $E\{\cdot\}$ represent the maximum operator and the mathematical expectation operator respectively and $\boldsymbol{x} = [x_0, x_1, \cdots, x_{N-1}]$.

By employing complementary cumulative distribution function (CCDF) [15], PAPR reduction performance can be described. The CCDF gives the probability that a number of OFDM signals exceed a given PAPR threshold and can be used for evaluating PAPR reduction performance of any PAPR reduction schemes, expressed as

$$\mathrm{CCDF}(N, \mathrm{PAPR}_0) = \Pr\{\mathrm{PAPR} > \mathrm{PAPR}_0\} = 1 - (1 - e^{-\mathrm{PAPR}_0})^N \tag{3}$$

where PAPR_0 denotes a given PAPR threshold.

For a discrete-time OFDM signal given in Eq. (1), it can be realized by employing an N-point inverse fast Fourier transform (IFFT), which induces that some peak powers may be lost. To avoid this problem, the oversampling is usually adopted. It is verified that the discrete-time OFDM signal with four times oversampling (i.e., $L = 4$) can approximate the real PAPR results [16], where L denotes the oversampling factor.

3 Conventional PTS

Firstly, after the input bit stream is mapped, the obtained complex sequence $\boldsymbol{X}$ is divided into several non-overlapped subblock sequences. Here, it is assumed that V is the number of subblock sequences. After the subblock partition is completed, V subblock sequences can be obtained, given by $\boldsymbol{X}_i, i = 1, 2, \cdots, V$. In this way, the input complex sequence $\boldsymbol{X}$ can be expressed by

$$\boldsymbol{X} = \sum_{i=1}^{V} \boldsymbol{X}_i \tag{4}$$

Then, by employing phase weighting factors for all the subblock sequences, the weighted subblock sequences can be combined to generate a candidate sequence, given by

$$\boldsymbol{x}' = \mathrm{IFFT}\left\{\sum_{i=1}^{V} b_i \boldsymbol{X}_i\right\} = \sum_{i=1}^{V} b_i \cdot \mathrm{IFFT}\{\boldsymbol{X}_i\} = \sum_{i=1}^{V} b_i \boldsymbol{x}_i \tag{5}$$

where $\boldsymbol{x}'$, $\boldsymbol{x}_i$ and b_i denote a candidate sequence, the ith subblock sequence in the time domain and the phase factor for weighting the ith subblock sequence respectively.

For C-PTS scheme, the phase weighting factor for the first subblock can be set to be one without any PAPR performance loss. Thus, if W phase weighting factors are allowed for weighting V subblock sequences, W^{V-1} candidate sequences can be achieved. Finally, the minimum PAPR value candidate sequence is chosen for transmitting. The block diagram of C-PTS scheme is shown in Fig. 1.

In the original OFDM system, for one input data sequence, only one candidate sequence is arguably generated and its CCDF can be expressed by Eq. (3). But for PTS scheme, W^{V-1} different candidate sequences can be obtained, then

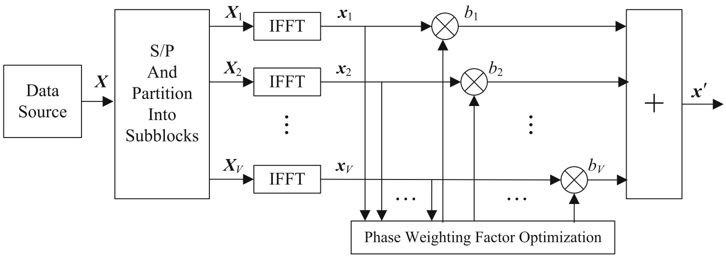

Fig. 1. Block diagram of conventional PTS

the CCDF of the chosen candidate sequence with the threshold PAPR_0 will become $[\Pr(\mathrm{PAPR} > \mathrm{PAPR}_0)]^{W^{V-1}}$. Obviously, by employing the PTS scheme, the probability of the PAPR exceeding some threshold PAPR_0 is lowered. That is to say, PAPR reduction performance of PTS scheme is decided by the number of generated candidate sequences. Assume that C is the number of candidate sequences, the CCDF of PTS can be given by

$$\begin{aligned}\mathrm{CCDF}_{\mathrm{PTS}} &= [\Pr(\mathrm{PAPR} > \mathrm{PAPR}_0)]^C \\ &= \left[1 - (1 - e^{-\mathrm{PAPR}_0})^N\right]^C\end{aligned} \tag{6}$$

In addition, for the sake of recovering the original input data correctly, the side information is required. By achieving this information, the receiver could know which allowed phase weighting factors has been used for weighting sub-block sequences. In pratical applications, the side information is transmitted accompanying with the selected OFDM candidate sequence.

4 Hybrid Interleaved-PTS

4.1 Ideas of Proposed Hybrid Interleaved-PTS Scheme

In proposed hybrid interleaved-PTS scheme, the alternate optimization is firstly adopted for simplifying phase weighting process of subblock sequences. As for the alternate optimization, it means that only the even subblock sequences need to be weighted by the allowed phase weighting factors and the odd ones remain unchanged. In this way, compared with C-PTS, the subblock phase weighting process is simplified and the significant reduction in computational complexity can be achieved. It is due to the fact that the number of candidate sequences is decreased when the alternate optimization is adopted. But for the same reason, PAPR reduction performance of proposed scheme is degraded.

After alternate optimization is completed, the number of candidate sequences generated at this stage can be given as follows.

$$\begin{cases} W^{\frac{V}{2}} & V \text{ is even} \\ W^{\frac{V-1}{2}} & V \text{ is odd} \end{cases} \tag{7}$$

where V denotes the number of subblock sequences and W is the number of allowed phase weighting factors.

To improve PAPR reduction performance of proposed hybrid interleaved-PTS, block interleaving is employed for the first subblock sequence. Specifically speaking, the first subblock sequence is partitioned into several blocks and then all the blocks can be permuted by using periodic or random order to generate different sequences. Assume that the original first subblock sequence in the time domain is expressed by $\boldsymbol{x}_1 = [x_{1,0}, x_{1,1}, \cdots, x_{1,i}, \cdots]$, where $x_{1,i}$ denotes the ith block in the first subblock sequence. After the permutation of all the blocks is performed, the original first subblock sequence becomes $\boldsymbol{x}'_1 = [x_{1,\theta(0)}, x_{1,\theta(1)}, \cdots, x_{1,\theta(i)}, \cdots]$, where $\{i\} \rightarrow \{\theta(i)\}$ is the one-to-one mapping. After the permutation is performed once, the first subblock sequence is changed. Thereupon, all the weighted even subblock sequences can be utilized again to obtain new candidate sequences. By doing this, PAPR reduction performance of proposed hybrid interleaved-PTS can be improved due to the fact that the number of candidate sequences is increased. It is worth mentioning that in the process of generating the new candidate sequences, no complex multiplication is required and only complex additions are needed for obtaining these candidate sequences, given as

$$\boldsymbol{y}' = \boldsymbol{y} - \boldsymbol{x}_1 + \boldsymbol{x}'_1 \tag{8}$$

where $\boldsymbol{y}'$, $\boldsymbol{y}$, $\boldsymbol{x}_1$ and $\boldsymbol{x}'_1$ denote a new candidate sequence, the candidate sequence from the stage of alternate optimization, the original first subblock sequence and the interleaved first subblock sequence respectively.

As mentioned above, the candidate sequences in proposed hybrid interleaved-PTS scheme are achieved by two stages, i.e., the alternate optimization and the block interleaving for the first subblock sequence. Finally, the one with the minimum PAPR among all the candidate sequences from two stages is chosen for transmission. The block diagram of proposed hybrid interleaved-PTS scheme is shown in Fig. 2.

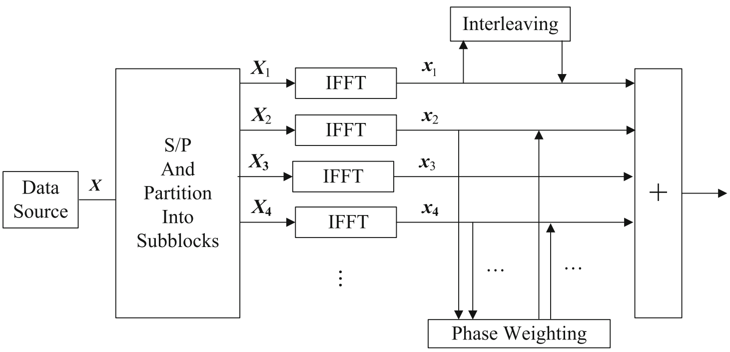

Fig. 2. Block diagram of proposed hybrid interleaved-PTS

For easily understanding the proposed hybrid interleaved-PTS scheme, the set of allowed phase weighting factors $\{j, -j\}$ (i.e. $W = 2$) and the number of subblock sequences $V = 4$ are taken as an example. In such conditions, eight candidate sequences cound be obtained in C-PTS. Thus, for proposed hybrid interleaved-PTS scheme, if the similar PAPR reduction performance is expected, the same number of candidate sequences must be achieved. The detailed process of proposed scheme is given as follows. Firstly, the alternate optimization is performed. Because only the even subblock sequences need to be weighted, the phase weighting factors for the odd ones are set to be one. At this stage, four phase weighting sequences can be obtained, given by

$$[1, j, 1, j], [1, -j, 1, j], [1, j, 1, -j], [1, -j, 1, -j]$$

That is to say, at the stage of alternate optimization, four candidate sequences $\boldsymbol{y}_i, i = 1, 2, 3, 4$ can be generated by using the above phase weighting sequences. To obtain the same number of candidate sequences as C-PTS, another four candidate sequences must be generated. Thereupon, the block interleaving for the first subblock sequence is employed. Here, two blocks obtained by partitioning the first subblock sequence are sufficient, i.e. $\boldsymbol{x}_1 = [\boldsymbol{x}_{1,1}, \boldsymbol{x}_{1,2}]$. Then, by permuting these two blocks in the first subblock sequence one time and utilizing all the weighted even subblock sequences again, four new candidate sequences can be obtained on the basis of Eq. (8), given by

$$\boldsymbol{y}_i = \boldsymbol{y}_{i-4} - \boldsymbol{x}_1 + \boldsymbol{x}'_1, i = 5, 6, 7, 8 \tag{9}$$

where $\boldsymbol{x}'_1 = [\boldsymbol{x}_{1,2}, \boldsymbol{x}_{1,1}]$ denotes the permuted first subblock sequence.

Thus, for proposed hybrid interleaved-PTS scheme, eight candidate sequences can be achieved by two stages. Since the proposed hybrid interleave-PTS scheme gets the same number of candidate sequences as C-PTS, these two schemes have similar PAPR reduction performance.

Moreover, in order to recovery the original input data successfully, the side information is also required in proposed hybrid interleaved-PTS scheme. Just as C-PTS, the same side information transmission method is adopted in proposed scheme.

4.2 Computational Complexity Analysis

Compared with C-PTS scheme, the subblock phase weighting process and the generation of parts of candidate sequences in proposed hybrid interleaved-PTS are different. For a fair comparison, it is assumed that the same number of candidate sequences is generated in both proposed hybrid interleaved-PTS and C-PTS. For these two schemes, if the number of subblock sequences is same, the same number of IFFT operations will be required. Therefore, in this section, the number of operations adopted in the subblock phase weighting process and the generation of candidate sequences is only taken into account. For OFDM systems, assume that L times oversampling is adopted, where L is the oversampling factor.

As mentioned above, for the given the number of subblocks sequences V and the number of allowed phase weighting factors W, W^{V-1} candidate sequences can be obtained in C-PTS. For C-PTS, $LN\,(V-1)$ complex additions and $LN\,(V-1)$ complex multiplications are required for generating each candidate sequence. Thus, in order to obtain all the W^{V-1} candidate sequences, $LN\,(V-1)\,W^{V-1}$ complex multiplications and $LN\,(V-1)\,W^{V-1}$ complex additions are required in C-PTS.

For proposed hybrid interleaved-PTS scheme, the candidate sequences involve two parts. The first part is achieved at the stage of alternate optimization and the number of candidate sequences in this part can be seen according to Eq. (7). The second part is achieved at the stage of the block interleaving for the first subblock sequence and it should be noted that only complex additions are required for obtaining the candidate sequences in this part. It is due to the fact that for the candidate sequences in the second part, no phase weighting process is involved.

As for the candidate sequences from the first part, because only the even subblock sequences need to be weighted by the allowed phase weighting factors, the number of complex multiplications needed for generating each candidate sequence can be given by

$$\begin{cases} \frac{V}{2}LN & V \text{ is even} \\ \frac{V-1}{2}LN & V \text{ is odd} \end{cases} \tag{10}$$

At the stage of the block interleaving for the first subblock sequence, because no complex multiplication is involved, only complex additions are needed for generating candidate sequences. In terms of Eq. (9), each candidate sequence in the second part requires $2LN$ complex additions.

Thus, computational complexity of proposed hybrid interleaved-PTS can be given as follows.

$$\text{Complex Mul.}: \begin{cases} \frac{V}{2}LNW^{\frac{V}{2}} & V \text{ is even} \\ \frac{V-1}{2}LNW^{\frac{V-1}{2}} & V \text{ is odd} \end{cases} \tag{11}$$

$$\text{Complex Add.}: \begin{cases} \left[(V-3)W^{\frac{V}{2}} + 2W^{V-1}\right]LN & V \text{ is even} \\ \left[(V-3)W^{\frac{V-1}{2}} + 2W^{V-1}\right]LN & V \text{ is odd} \end{cases} \tag{12}$$

5 Simulation Results and Analysis

To show the PAPR reduction performance of proposed hybrid interleaved-PTS scheme, the corresponding computer simulations are done. An OFDM system with 256 subcarriers (i.e., $N = 256$) is adopted. In simulations, the set of phase weighting factors $\{j, -j\}$ (i.e., $W = 2$) is used for performing the subblock phase weighting process. Moreover, to approach the real PAPR reduction performance, the oversampling factor $L = 4$ is employed.

Figure 3 gives PAPR reduction performance of proposed hybrid interleaved-PTS employing QPSK modulation with the number of subblock sequences $V = 4, 8$. For a comparison, PAPR reduction performances of AO-PTS and C-PTS are also given in Fig. 3. For each value of V, the number of candidate sequences in proposed hybrid interleaved-PTS is the same as that in C-PTS.

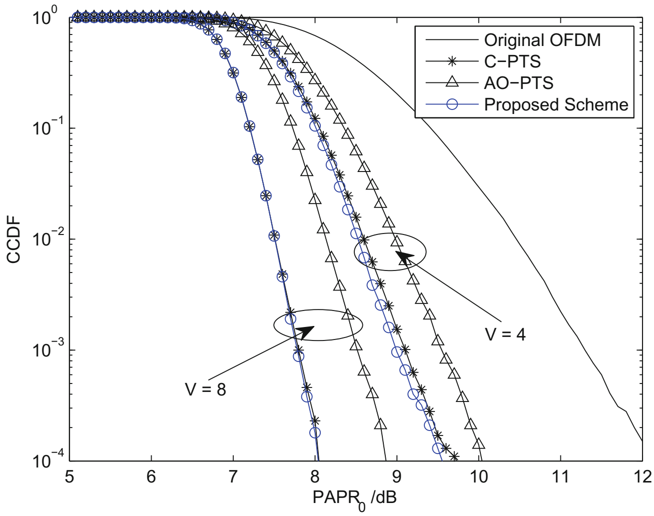

Fig. 3. CCDFs of proposed hybrid interleaved-PTS, AO-PTS and C-PTS

It is shown in Fig. 3 that the CCDF curves of the proposed hybrid interleaved-PTS scheme and C-PTS scheme are almost overlapped, which means that these two schemes have similar PAPR reduction performance. But for AO-PTS scheme, its PAPR reduction performance is much worse than those of C-PTS scheme and proposed hybrid interleaved-PTS scheme, which is due to the fact that among these three schemes, the number of candidate sequences generated in AO-PTS is the least.

As to computational complexity, a comparison between proposed hybrid interleaved-PTS and C-PTS in terms of complex multiplication and complex addition is shown in Table 1.

Table 1. Comparison of complexity between proposed hybrid interleaved-PTS and C-PTS

W	V	Complex Mul. (%)	Complex Add. (%)
2	4	66.7	16.7
2	8	92.9	62.5

As we can see in Table 1, proposed hybrid interleaved-PTS gains lower computational complexity than C-PTS. For instance, if $W = 2$ and $V = 8$, 92.9% complex multiplication reduction and 62.5% complex addition reduction can be achieved. Moreover, if an increase in the number of subblock sequences is shown, proposed hybrid interleaved-PTS could gain more reduction in computational complexity.

6 Conclusion

In this paper, a hybrid interleaved-PTS scheme with low computational complexity is proposed for reducing PAPR in OFDM systems. In proposed hybrid interleaved-PTS scheme, alternate optimization and block interleaving are employed for reducing computational complexity and improving PAPR reduction performance respectively. With the extensive computer simulations, the proposed hybrid interleaved-PTS scheme can achieve dramatic reduction in computational complexity and similar PAPR reduction performance compared with C-PTS.

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