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A novel reduced complexity optimized PTS technique for PAPR reduction in wireless OFDM systems

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ABSTRACT

In this paper, we propose a novel low complexity Partial Transmit Sequence (PTS) technique employing Random phase sequence matrix (RPSM) for peak to average power ratio (PAPR) reduction in orthogonal frequency division multiplexing (OFDM) systems. The main goal of our suggested scheme is to achieve the optimum phase sequence matrix to minimize PAPR and simultaneously reduce the computational complexity by decreasing the number of Inverse Fast Fourier Transform (IFFT) operations required. Lower PAPR reduces the complexity of Digital to Analog converters (DAC) and increases the efficiency of power amplifiers. Analytical expressions for Complementary Cumulative Distribution Function (CCDF), Number of subcarriers, subblocks and Total computational complexity are derived. Simulation results match closely with the analytical results. It is demonstrated that a favorable tradeoff can be achieved between the reduction of PAPR and computational complexity. It is observed that the suggested modified PTS technique outperforms the traditional PTS (T-PTS) technique.

1. Introduction

The increase in demand for multimedia services and high data rates needs the use of prominent transmission techniques. Orthogonal Frequency Division Multiplexing is a scheme best suited to mitigate frequency selective fading [1]. Hence OFDM is applied in different wireless environments such as Worldwide Interoperability for Microwave Access (WiMAX), Long term evolution (LTE), Digital video Broadcasting (DVB) and HIPERLAN/2. But one of the major disadvantages of OFDM signals is high Peak to Average power ratio of the signal transmitted. High value of PAPR increases the complexity of Digital to Analog converters (DAC) and results in power amplifier efficiency degradation. The transmission of high PAPR signal through non-linear power amplifier results in spectral broadening increasing the dynamic range of the Digital to Analog converters and there by increases the cost of the system. The main goal of the wireless OFDM system is to achieve minimum PAPR. In this paper, we develop novel Partial Transmit Sequence technique with Random phase sequence matrix which results in PAPR reduction with reduced complexity.

To overcome the problem of PAPR, several techniques for decreasing the PAPR have been proposed. The authors of [8] presented an approach which processes the data using Modified SLM technique after the IFFT operations to decrease the PAPR of OFDM systems. A low complexity PAPR reduction for OFDM systems using modified widely linear SLM scheme is suggested in [9]. However this system does not achieve significant reduction in complexity and the PAPR reduction performance is poorer compared to that of the conventional scheme. Novel selected mapping schemes with reduced complexity are developed in [10]. Even though the computational complexity is substantially reduced, PAPR reduction performance is inferior to that of traditional SLM scheme. SLM scheme for reduction in PAPR without the need of side information is proposed in [12]. But SLM technique requires more IFFT operations which increases the implementation complexity. Reduction of PAPR in OFDM systems using Tone Reservation is proposed in [13–15] while PAPR reduction using clipping technique is cited in [16–18]. Low complexity Tone reservation with null subcarriers to decrease PAPR in WiMAX system is suggested in [13].

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However the searching complexity increases for this scheme with the increase in number of subcarriers. A tone reservation algorithm based on Cross-Entropy method for decreasing PAPR is proposed in [14]. Here Cross-Entropy method is introduced to determine the suboptimum values of the peak reduction carriers. But this scheme does not reduce PAPR and complexity at the same time. A non-linear optimization approach to search the optimal combination of peak reduction tone sets is presented in [15]. The authors of [16] proposed PAPR reduction techniques with low complexity for clipping and quantization noise cancellation in direct detection O-OFDM systems. But the searching complexity is not considered in this technique and it does not achieve significant reduction in PAPR. PAPR reduction using an optimization method based adaptive iterative clipping is proposed in [17] while PAPR reduction using pre-coding with clipping and filtering is suggested in [18]. Both of these schemes do not consider the complexity reduction. Even though clipping is easy to implement, it may result in-band and out-of-band interferences while eliminating the orthogonality among the subcarriers.

PAPR reduction methods using coding techniques are suggested in [19–22]. Mahmudul Hasan proposed a technique for PAPR reduction in [19] using Linear predictive coding (LPC) which uses signal whitening property of LPC as a pre-processing step in OFDM systems. PAPR reduction using Zadoff-chu matrix transform (ZCMF) pre-coding based OFDM system is presented in [20] to allow the Radio frequency amplifier to operate near its saturation level. PTS algorithm using Reed-Muller (RM) codes for error correction and PAPR reduction is proposed in [21] which shows that RM codes in cyclic ordering achieve better performance than RM codes in natural ordering. Reduction in PAPR by integrating SLM, Constellation extension and RM codes to construct a Modified SLM technique is presented in [22]. This technique has the capability of error correction and also does not need extra side information to be transmitted. However, the bandwidth efficiency of the coding techniques discussed in [19–22] is decreased by reducing the code rate. For obtaining the better codes and preparing huge look up tables for encoding and decoding, complexity becomes more. Moreover the aspect of computational complexity is not considered in the coding techniques. PAPR reduction using Modified Active Constellation Extension (ACE) in generalized multicarrier signals is suggested in [23]. A residue number system (RNS) based OFDM parallel transmission scheme for reducing PAPR is proposed in [24]. But the hardware complexity of the methods suggested in [23,24] increases due to repeated search. PAPR reduction using Hadamard Transform is presented in [25] which does not reduce PAPR to the desirable level and so it may result in degradation in the power amplifier efficiency.

2. Related work

PTS technique is an efficient way to reduce PAPR as it uses an iterative routine to find the phase factors which are optimum without the restriction on the amount of subcarriers. PTS scheme operates generally in time domain while SLM scheme operates in frequency domain. PAPR reduction employing various PTS techniques are discussed in [2–7]. Decrease in PAPR of OFDM signals employing partial transmit sequences is proposed in [2]. But the conventional or traditional PTS algorithm requires an exhaustive search of the allowed phase factors which increases the complexity. PAPR reduction employing Interleaved PTS scheme which makes use of conjugate property of DFT is suggested in [3]. However the PTS scheme using random phase sequence has better performance in reducing PAPR compared to the interleaved scheme. A PAPR reduction algorithm based on tree-structured searching technique which uses PTS scheme is proposed in [4]. Though complexity is reduced using this scheme, the reduction in the number of IFFT operations is not considered. The reduction in PAPR of OFDM signals by using PTS with real valued genetic approach is proposed in [5]. But this scheme yields the same PAPR performance as that of exhaustive PTS scheme. Low density parity check coded OFDM systems using PTS scheme for PAPR reduction are developed in [6]. The drawback of this scheme is that it does not consider the computational complexity. PTS subblocking technique using only partial IFFT's for complexity reduction is cited in [7]. Though it achieves complexity reduction, the PAPR performance is same as that of original PTS scheme which results in increase in the complexity of power amplifiers which in turn reduces their efficiency which is a drawback.

In this paper, a novel reduced complexity PTS technique which makes use of Random phase sequence matrix is proposed. A significant feature is that the analytical expressions for certain important parameters such as complementary cumulative distribution function, total complexity are derived. The analytical results derived accurately match with the simulation results. Our contribution to this paper aims at achieving simultaneously good PAPR reduction and reduced computational complexity.

This paper is organized as follows: In Section 3, wireless OFDM system is characterized and PAPR, CCDF are formulated. The proposed PTS technique is discussed in Section 4 and in Section 5, the theoretical analyses are carried out by deriving the expressions for CCDF, number of subcarriers, subblocks and total computational complexity for the suggested scheme. Results and discussions are presented in Section 6 while Section 7 concludes the paper.

3. Characterization of wireless OFDM system and formulation of PAPR, CCDF

3.1. OFDM system characterization

In OFDM systems, modulation of OFDM symbols is performed in the transmitter section and next Inverse FFT operation is carried out to obtain time domain signals. In the receiver section, FFT operation is performed to convert the signals into frequency domain followed by demodulation to convert into the original signals. The baseband signal can be formulated as

$$s(n) = \frac{1}{\sqrt{M}} \sum_{k=0}^{M-1} S(k) \exp\left(\frac{j2\pi nk}{M}\right), \quad 0 \leqslant n \leqslant M-1 \tag{1}$$

where $S(k)$ is the modulated data signal expressed in frequency domain, M is the number of subcarriers. PAPR finds its significance for enabling power amplifier to operate in linear region, for generating error free OFDM symbols at the transmitted output.

3.2. Peak to average power ratio

For getting better approximation of PAPR, oversampling by 'L' times is performed for OFDM symbols. The oversampled signal in time domain is formulated as

$$s(n) = \frac{1}{\sqrt{M}} \sum_{k=0}^{M-1} S(k) \exp\left(\frac{j2\pi nk}{LM}\right), \quad 0 \leqslant n \leqslant LM-1 \tag{2}$$

The peak to average power ratio of the OFDM signal is defined as the ratio of maximum instantaneous power to the average power. It is formulated mathematically as

$$PAPR[s(n)] = \frac{\max\limits_{0 \leqslant n \leqslant LM-1} \left[|s(n)|^2\right]}{E[|s(n)|^2]} \tag{3}$$

Here E [·] specifies the expectation operator.

3.3. Complementary cumulative distribution function

If the distribution of power of output OFDM signals is found, the probability that the instantaneous power exceeds the predefined threshold value can be obtained. It is done by finding the CCDF for various values of PAPR.

The CCDF is formulated and expressed as

$$CCDF = Pr(PAPR > PAPR_0) \tag{4}$$

4. Proposed PTS technique

4.1. Review of conventional PTS scheme

The partial transmit sequence scheme is a probabilistic technique in time domain to obtain minimum PAPR for transmission. The traditional PTS scheme is discussed in [2].

Let S denote the random signal in frequency domain. Now S is partitioned into U disjoint subblocks represented by $\{S^{(u)}, u = 1, 2, \ldots U\}$ where $S^{(u)}$ is given by

$$S^{(u)} = \left[S_0^{(u)} S_1^{(u)} \ldots S_{M-1}^{(u)}\right] \tag{5}$$

Now S can be expressed as

$$S = \sum_{u=1}^{U} S^{(u)} \tag{6}$$

The phase rotation factors are given by

$$c_u = e^{j\theta_u}, \quad u = 1, 2 \ldots U \tag{7}$$

In conventional PTS scheme, the elements of every row of phase factor matrix c possess the equal value. It is expressed as

$$c = \begin{bmatrix} c_1 & \cdots & c_1 \\ \vdots & \vdots & \vdots \\ c_U & \cdots & c_U \end{bmatrix} \tag{8}$$

The matrix specified in (8) has the order $U \times M$. Usually, c is assumed to be known at both transmitter and receiver. The elements of the matrix in (8) are applied to the U subblocks and the corresponding signals in frequency domain are given by

$$S' = \sum_{u=1}^{U} c_u S^{(u)} \tag{9}$$

Next IFFT operations are applied to each subblock and the appropriate signals in time domain are obtained as

$$S' = IFFT\left\{\sum_{u=1}^{U} c_u S^{(u)}\right\} = \sum_{u=1}^{U} c_u s^{(u)} \tag{10}$$

The phase vector is selected so as to reduce the PAPR. The optimization parameter is determined next and the time domain signal having the least value of PAPR is transmitted.

4.2. Novel modified PTS technique with RPSM

The suggested novel PTS technique is based on determining a total values of 'M' from the given phase factors. The modified phase sequence is represented in the matrix form as

$$\hat{c} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,M} \\ \vdots & \vdots & \vdots \\ c_{U,1} & \cdots & c_{U,M} \end{bmatrix} \tag{11}$$

Here M values are computed U times periodically and the rows of modified phase matrix have distinct values. The values are chosen from the allowed phase factors in random manner. For the proposed technique, we follow different approach of finding the optimized phase factors. Let W be the number of phase factors that are allowed.

Assuming U subblocks, to find the optimization parameter, we perform repeated search for a total of $(U-1)$ phase factors as the unity phase factor remains fixed in all cases. Since W is the phase factor allowed, the number of iterations 'Q' required for the proposed PTS scheme is given by

$$Q = BW^{U-1} \tag{12}$$

B is an important parameter that specifies the trade-off between PAPR and computational complexity. Higher value of B leads to higher PAPR reduction while lower value of B results in smaller PAPR reduction. The traditional scheme offers good performance for reducing the PAPR but requires repeated search for computing the optimum factors relating to phase and hence the complexity becomes higher by increasing the number of subcarriers.

The Random phase sequence matrix is generated by augmenting the matrix in (11). It is given by

$$\hat{c} = \begin{bmatrix} c_{1,1} & \cdots & c_{1,M} \\ \vdots & \vdots & \vdots \\ c_{U,1} & \cdots & c_{U,M} \\ c_{U+1,1} & \cdots & c_{U+1,M} \\ \vdots & \vdots & \vdots \\ c_{Q,1} & \cdots & c_{Q,M} \end{bmatrix} \tag{13}$$

where the matrix specified in (13) has the order $Q \times M$. The augmented Interleaved and Adjacent phase sequence matrices are given by

$$\hat{c} = \begin{bmatrix} c_{1,1}, \cdots, c_{1,M/Q} & \cdots & c_{1,1}, \cdots, c_{1,M/Q} \\ \vdots & \vdots & \vdots \\ c_{U,1}, \cdots, c_{U,M/Q} & \cdots & c_{U,1}, \cdots, c_{U,M/Q} \\ c_{U+,1,1}, \cdots, c_{U+1,M/Q} & \cdots & c_{U+1,M}, \cdots, c_{U+1,M/Q} \\ \vdots & \vdots & \vdots \\ c_{Q,1}, \cdots, c_{Q,M/Q} & \cdots & c_{Q,1}, \cdots, c_{Q,M/Q} \end{bmatrix} \tag{14}$$

$$\hat{c} = \begin{bmatrix} c_{1,1}, \cdots, c_{1,1} & \cdots & c_{1,1}, \cdots, c_{1,M/Q} \\ \vdots & \vdots & \vdots \\ c_{U,1}, \cdots, c_{U,1} & \cdots & c_{U,M/Q}, \cdots, c_{U,M/Q} \\ c_{U+,1,1}, \cdots, c_{U+1,1} & \cdots & c_{U+1,M/Q}, \cdots, c_{U+1,M/Q} \\ \vdots & \vdots & \vdots \\ c_{Q,1}, \cdots, c_{Q,1} & \cdots & c_{Q,M/Q}, \cdots, c_{Q,M/Q} \end{bmatrix} \tag{15}$$

The matrices in (14) and (15) have order $Q \times M$. The RPSM in (13) takes into account the lesser number of iterations 'Q' for searching the optimum phase factors compared to the traditional PTS and is simpler to implement. The PAPR reduction performance using RPSM is better compared to that using Interleaved and Adjacent phase sequence matrices. Hence we make use of RPSM in the simulation of the proposed PTS technique. The low complexity Fractional subblocking scheme for PTS for PAPR reduction suggested in [7] only reduces the computational complexity but PAPR reduction performance is almost same as the traditional PTS scheme. But in our suggested scheme, we observe that the PAPR reduction performance is improved and simultaneously, the total computational complexity is also reduced.

Fig. 1 shows the block diagram for the proposed PTS technique. The incoming samples are converted into parallel form and partitioned into subblocks. S denotes the random signal in frequency domain partitioned into U subblocks as represented using (6). The subsequent signals of the subblock partitioned frequency domain signals are transformed into time domain by applying IFFT operations. These signals are multiplied with the modified phase sequence and the resultant signal is expressed as

$$\hat{s} = IFFT\left\{\sum_{u=1}^{U}\hat{c}_u S^{(u)}\right\} = \sum_{u=1}^{U}\hat{c}_u s^{(u)} \tag{16}$$

The time domain symbols are then applied to the weighting factor optimization block that gives the optimum parameter. The weighting factor optimization process is carried out in this block and the optimization parameter is chosen with the following condition specified as

$$[\tilde{c}_1 \ldots \tilde{c}_U] = \underset{0 \leqslant n \leqslant LM-1}{\text{argmin}}\left[\max\left|\sum_{u=1}^{U}\hat{c}_u s^{(u)}(n)\right|\right] \tag{17}$$

Finally multiplication of the optimized parameter is performed with the input signal such that the resultant signal with minimum PAPR is transmitted. The corresponding signal is expressed as

$$\tilde{s} = \sum_{u=1}^{U}\tilde{c}_U s^{(u)} \tag{18}$$

5. Analytical expressions for the proposed PTS scheme

5.1. Analytical expression for CCDF

In this section, we derive the analytical expressions for CCDF, number of subcarriers, subblocks and the total complexity for the proposed method. The amplitude of an OFDM signal follows Rayleigh distribution while the power has chi-square distribution having zero mean and two degrees of freedom. Let M be the number of subcarriers for the OFDM system. The cumulative distribution function (CDF) of the system expressed as

$$F(z) = \int_0^z f_S(s)ds \tag{19}$$

where $f_S(s)$ is the Rayleigh distributed Probability density function. So, (19) can be represented as

$$F(z) = \int_0^z \frac{s}{\sigma^2}\exp\left(-\frac{s^2}{2\sigma^2}\right)ds \tag{20}$$

where σ^2 is the variance and σ is the standard deviation of the random variable 'S'.

The integral in (20) can be evaluated by making the appropriate substitution as

$$\frac{s^2}{2\sigma^2} = k \tag{21}$$

The integral in (20) becomes

$$F(z) = \int_{k=0}^{\frac{z^2}{2\sigma^2}} \exp(-k)dk \tag{22}$$

Evaluating the integral in (22) yields the result as

$$F(z) = 1 - \exp\left(-\frac{z^2}{2\sigma^2}\right) \tag{23}$$

or

$$F(z) = 1 - \exp(-p_0) \tag{24}$$

where $p_0 = \frac{z^2}{2\sigma^2}$ represents the PAPR threshold. Assuming that the signal samples are mutually independent, the CDF of an OFDM data block with M subcarriers is given by

$$F(z) = [1 - \exp(-p_0)]^M \tag{25}$$

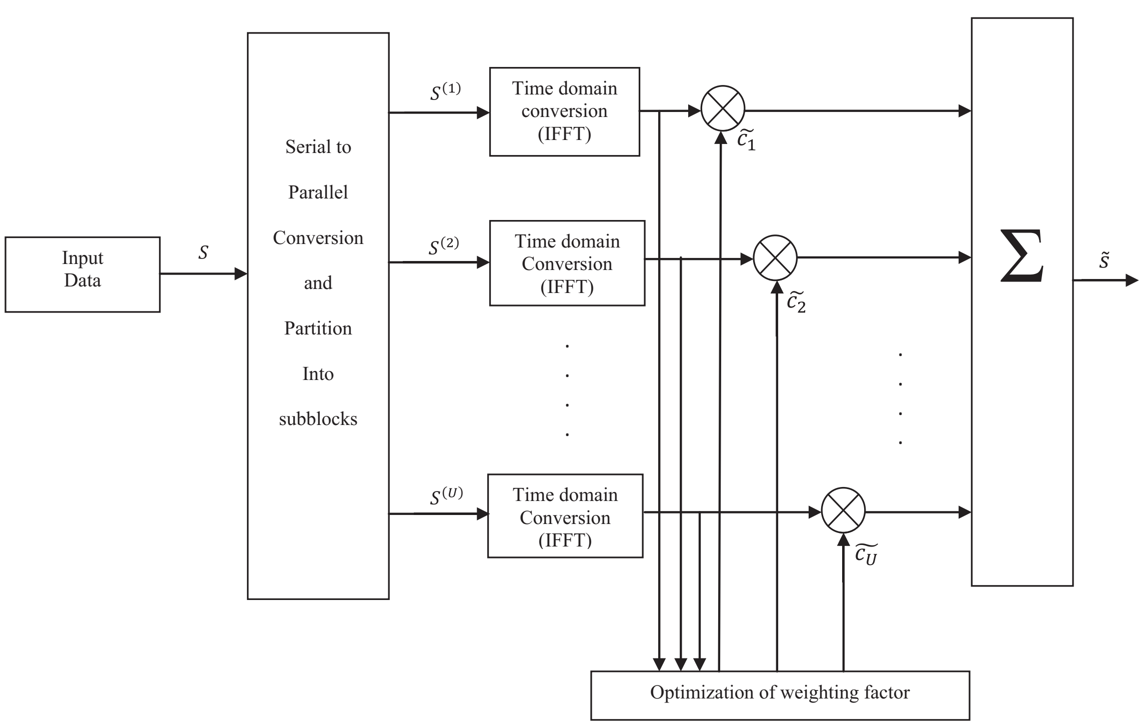

Figure 1. Block diagram of proposed PTS technique with RPSM.

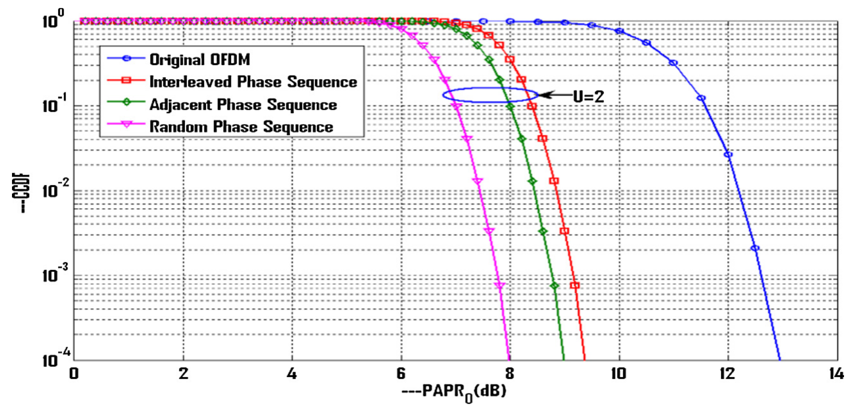

Figure 2. CCDF vs. PAPR threshold using random, interleaved and adjacent phase sequences.

From (25), the CDF can be expressed as

$$P(PAPR \leqslant p_0) = [1 - \exp(-p_0)]^M \tag{26}$$

The complementary CDF(CCDF) is given by

$$P(PAPR > p_0) = \left\{1 - [1 - \exp(-p_0)]^M\right\} \tag{27}$$

The CCDF of PAPR for oversampled signal as suggested in [26] can be written as

$$P(PAPR > p_0) = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\} \tag{28}$$

In (28) α is a parameter related to oversampled signal. It is also specified in [26] that $\alpha = 2.8$ is a good approximation for the oversampling factor of 4.

For T-PTS scheme with U subblocks, if the phase rotated data blocks of OFDM are independent and uncorrelated, the CCDF of PAPR of the OFDM signal after applying PTS technique is given by

$$P(PAPR_{PTS}(U) > p_0) = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\}^U \tag{29}$$

Now (29) can be represented as

$$CCDF_{PTS} = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\}^U \tag{30}$$

Since we make use of a modified phase sequence in the optimization of weighting factor, the CCDF of the proposed PTS technique can be expressed as

$$CCDF_{proposed\ PTS} = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\}^{\gamma U} \tag{31}$$

where the parameter γ in (31) is a parameter whose value lies in the range 0–1. This parameter is used in plotting the analytical results in Figs. 3–6.

5.2. Analytical expression for the number of subcarriers and number of subblocks

Consider an OFDM system with M subcarriers and U subblocks. The CCDF in terms of PAPR from (28) by designating CCDF as ρ is represented as

$$\rho = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\} \tag{32}$$

Since $\exp(-p_0)] \ll 1$ (as $p_0 > 0$), (32) can be approximated as

$$\rho = \{1 - [1 - \alpha M \exp(-p_0)]\} \tag{33}$$

or

$$\rho = \alpha M \exp(-p_0) \tag{34}$$

The number of subcarriers 'M' from (34) can be expressed as

$$M = \frac{\rho \exp(p_0)}{\alpha} \tag{35}$$

We see that (35) specifies the relation between the number of subcarriers and PAPR threshold.

Next consider the proposed PTS technique whose analytical expression for CCDF is derived in (31). Designating ρ' as the CCDF, (31) can be expressed as

$$\rho' = \left\{1 - [1 - \exp(-p_0)]^{\alpha M}\right\}^{\gamma U} \tag{36}$$

As specified in (33) and (34), (36) can be approximated as

$$\rho' = [\alpha M \exp(-p_0)]^{\gamma U} \tag{37}$$

Now (37) can be represented as

$$(\alpha M)^{\gamma U} = \rho' \exp(p_0 \gamma U) \tag{38}$$

Applying logarithms on both sides of (38), we obtain

$$\gamma U \ln(\alpha M) = \ln(\rho') + p_0 \gamma U \tag{39}$$

which implies that (39) can be expressed as

$$\ln(\alpha M) = \frac{\ln(\rho')}{\gamma U} + p_0 \tag{40}$$

Therefore the expression for number of subcarriers is

$$M = \frac{1}{\alpha} \exp\left[\frac{\ln(\rho')}{\gamma U} + p_0\right] \tag{41}$$

We see from (41) that number of subcarriers increases if PAPR increases. From (40), the expression for PAPR can be expressed as

$$p_0 = \ln(\alpha M) - \frac{\ln(\rho')}{\gamma U} \tag{42}$$

which denotes that reduction of PAPR occurs if the number of subcarriers decreases by fixing the number of subblocks U and CCDF ρ'.

From (42), if the number of subcarriers M and CCDF ρ' are fixed, PAPR decreases as the number of subblocks increases.

The expression for the number of subblocks from (42) is

$$U = \frac{1}{\gamma}\left(\frac{\ln(\rho')}{\ln(\alpha M) - p_0}\right) \tag{43}$$

The analytical expressions derived in (41) and (43) specify the relation among PAPR, number of subcarriers and number of subblocks.

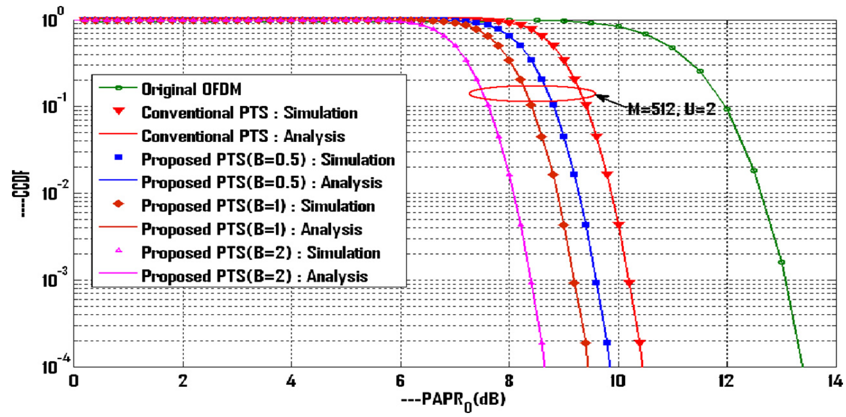

Figure 3. PAPR performance for traditional PTS and proposed PTS schemes for M = 512, U = 2.

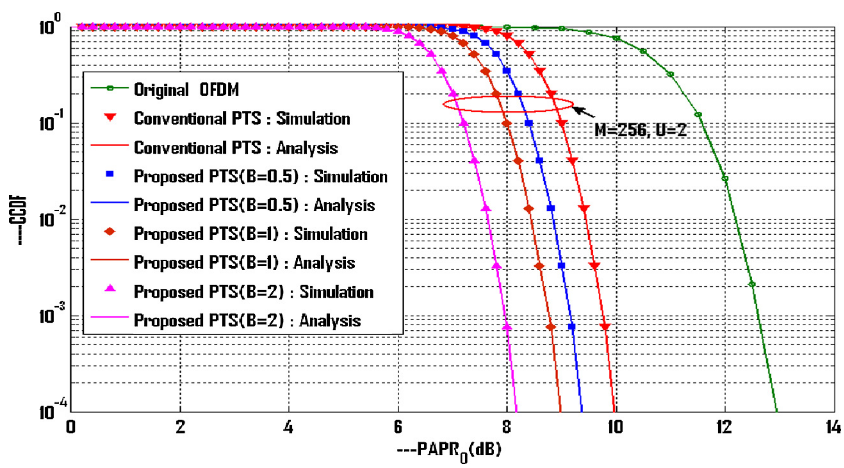

Figure 4. PAPR performance for traditional PTS and proposed PTS schemes for M = 256, U = 2.

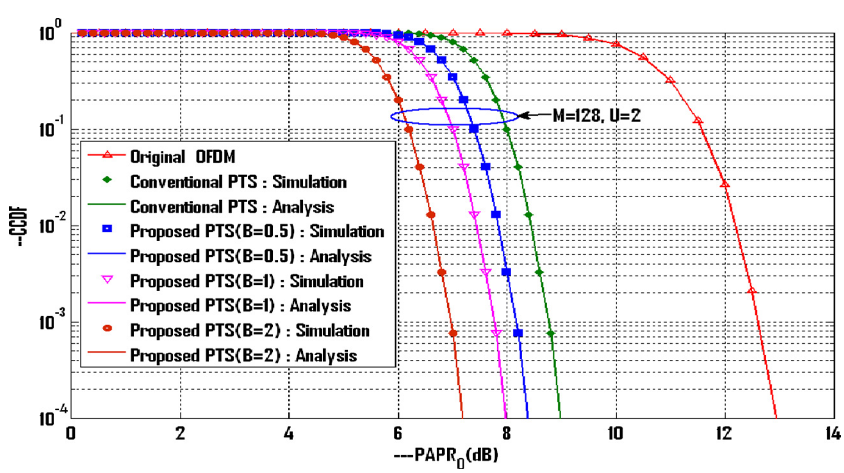

Figure 5. PAPR performance for traditional PTS and proposed PTS schemes for M = 128, U = 2.

5.3. Analytical expression for total computational complexity

Consider the proposed PTS scheme that has M subcarriers and U subblocks. The total computational complexity is always equal to the sum of the total number of IFFT operations required and the complexity of the searching method.

The total number of IFFT operations required for our suggested method is the sum of number of complex additions and complex multiplications. We know that for a standard IFFT flow graph, the number of complex additions required for an IFFT length of M is $M\log_2 M$ and the number of complex multiplications are $\frac{M\log_2 M}{2}$. For U subblocks, the number of complex additions and multiplications required are $UM\log_2 M$ and $\frac{UM\log_2 M}{2}$ respectively. Since the proposed method requires exactly half of the total complex additions and multiplications, this factor is given by

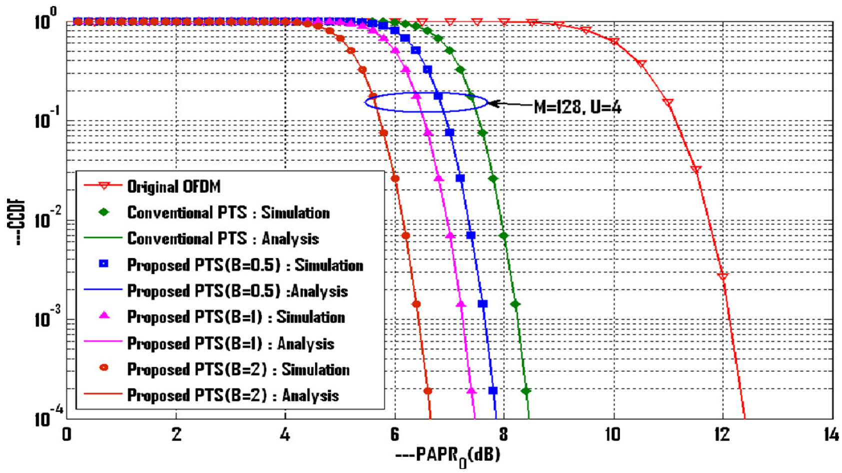

Figure 6. PAPR performance for traditional PTS and proposed PTS schemes for M = 128, U = 4.

$$T_1 = \frac{3UM\log_2 M}{4} \tag{44}$$

As the proposed scheme requires the iterations as specified in (12), the total complexity of the searching method taking into account the number of subcarriers and subblocks is

$$T_2 = (BW^{U-1})(UM) \tag{45}$$

Substituting (12) in (45), we obtain

$$T_2 = QUM \tag{46}$$

The total computational complexity of our suggested PTS scheme is obtained by adding (44) and (46). If T denotes the total computational complexity, it is given by

$$T = T_1 + T_2 = \frac{3UM\log_2 M}{4} + QUM \tag{47}$$

We make use of (47) in the computation of total complexity in Section 6.2.

6. Results and discussion

6.1. PAPR performance

In order to observe the performances of the proposed PTS and traditional PTS schemes, simulations have been performed using MATLAB software by considering an OFDM system employing Quadrature phase shift keying (QPSK) modulation. The number of subcarriers 'M' is set to 128,256,512. The number of subblocks 'U' is considered as 2, 4 and the number of OFDM symbols generated is 50,000. For the proposed PTS scheme, the PAPR is evaluated for three values of trade-off factors, B = 0.5, 1, 2. The oversampling factor 'L' is set to 4. To validate the accuracy of the analytical expressions derived, analytical CCDF's are plotted along with the simulation results in Figs. 3–6. The expressions for CCDF of traditional PTS and proposed PTS schemes derived in Section 5.1 using (30) and (31) are used for analysis. Different parameters in the analysis are $\alpha = 2.8$, $\gamma = 0.52, 0.76$, M = 128, 256, 512 and U = 2, 4.

The CCDF of PAPR of original OFDM is plotted first in Figs. 3–6. The simulation results are compared with that of analytical results for conventional PTS and proposed PTS schemes for B = 0.5, 1, 2.

Fig. 2 shows the CCDF vs. PAPR plot using Interleaved, Adjacent and Random phase sequences respectively for the number of subblocks U = 2. It is clear from the figure that the PAPR performance using Random phase sequence is superior compared to that of Interleaved and Adjacent phase sequences. Hence we employ Random phase sequence in further simulation results.

Fig. 3 shows the CCDF vs. PAPR plot with M = 512, U = 2. The simulation is performed for generating the CCDF vs. PAPR plot for conventional and Proposed PTS schemes with B = 0.5, 1, 2. The CCDF of original OFDM is plotted first. We observe that the PAPR reduces as B increases. The PAPR values at CCDF of 10^{-4} for B = 0.5, 1, 2 are 9.8 dB, 9.3 dB and 8.4 dB respectively.

Fig. 4 shows the CCDF vs. PAPR plot for M = 256, U = 2 for traditional PTS and proposed PTS schemes with B = 0.5, 1, 2. The simulation results denote that the PAPR decreases as B increases. The PAPR at a CCDF of 10^{-4} for B = 0.5, 1, 2 are 9.3 dB, 8.9 dB and 8.1 dB. We see that analytical results closely match with simulation results for both traditional PTS and proposed PTS techniques. The proposed method reduces PAPR effectively compared to that of traditional PTS and also reduction in PAPR is improved compared to that of T-PTS scheme.

The CCDF vs. PAPR plot for M = 128, U = 2 is shown in Fig. 5. The analytical results are validated with that of simulation results for conventional PTS scheme and proposed PTS scheme for B = 0.5, 1, 2. For plotting the analytical results, we consider $\gamma = 0.52$ for Figs. 3–5 and $\gamma = 0.76$ for Fig.6.

From Fig. 5, the PAPR values at CCDF of 10^{-4} are 0.7 dB, 1.1 dB and 2.1 dB lower than those for traditional PTS. Fig. 6 shows the CCDF vs. PAPR plot for M = 128, U = 4 for the same set of values of B. Here also PAPR decreases as B increases. We see from Figs. 5 and 6 that PAPR performance is improved for our proposed method compared to that of traditional PTS scheme. It is clear that the simulation results closely coincide with the analytical results. The decrease in PAPR in Fig. 6 is better than that in Fig. 5 which denotes that PAPR decreases with the increase in the number of subblocks.

For example for M = 256, U = 2 and B = 1, the PAPR at CCDF of 10^{-4} is 9.0 dB in Fig. 4 where as for M = 128, U = 2 and B = 1, the PAPR is 8.1 dB in Fig. 5. The expression derived in (41) justifies these results. For M = 128, U = 4 and B = 1, the PAPR value is 7.5 dB in Fig. 6. The expression derived in (43) justifies this result.

The relation between PAPR and number of subcarriers is derived in Section 5.2 using (41). From the results presented in Figs. 3–5, the PAPR values with different subcarriers for T-PTS and Proposed PTS schemes with B = 0.5, 1 and 2 are shown in Table 1. Here we observe that PAPR decreases as the number of subcarriers decreases. We also observe from Table 1 that PAPR reduces with the increase in the trade-off factor B.

6.2. Computational complexity

Here, Computational complexity reduction ratio (CCRR) is defined and formulated first and then the computational complex-

Table 1
PAPR values for M = 128, 256, 512 at CCDF of 10^{-4}.

Number of subcarriers (M)	$PAPR_0$ (dB)			
	T-PTS	Proposed PTS (B = 0.5)	Proposed PTS (B = 1)	Proposed PTS (B = 2)
128	9.2	8.5	8.1	7.1
256	10	9.3	8.7	8.1
512	10.4	9.8	9.3	8.5

Table 2
Complexity of T-PTS and proposed PTS with M = 128, 256, 512 and U = 2.

Number of subcarriers (M)	Total complexity			
	T-PTS	Proposed PTS (B = 0.5)	Proposed PTS (B = 1)	Proposed PTS (B = 2)
128	3712	1600	1856	2368
256	8192	3584	4096	5120
512	17,920	7936	8960	11,008

Table 3
CCRR for proposed PTS with M = 128, 256, 512 and U = 2.

Number of subcarriers (M)	CCRR		
	Proposed PTS (B = 0.5) (%)	Proposed PTS (B = 1) (%)	Proposed PTS (B = 2) (%)
128	56.89	50	36.21
256	56.25	50	37.48
512	55.71	50	38.57

ity and CCRR for the proposed method are determined and compared with that of T-PTS technique.

6.2.1. Computational complexity reduction ratio (CCRR)

An important parameter which is related to the computational complexity is the computational complexity reduction ratio which is defined as

$$CCRR = \left(1 - \frac{complexity\ of\ the\ proposed\ scheme}{complexity\ of\ the\ C - PTS\ scheme}\right) \times 100\% \quad (48)$$

It gives the reduction in percentage of complexity by employing the proposed scheme with respect to the traditional PTS scheme. Using CCRR we can estimate the performance of a system. Higher percentage of CCRR specifies good performance of the proposed scheme compared to the traditional scheme. It is also used to compare the complexity of the proposed scheme.

It is also used to compare the complexity of the proposed scheme for different values of the trade-off factor.

For T-PTS technique, we use the following equation for complexity calculations specified in [11] as

$$T = \frac{3UM\log_2 M}{2} + 2UW^{U-1}M \quad (49)$$

The first term in (49) represents the number of IFFT operations which is the sum of total number of complex additions and complex multiplications. The second term in (49) represents searching complexity of the algorithm. For the proposed PTS technique, we use the total complexity equation specified in (47) derived in Section 5.3 to perform the complexity calculations.

Total complexity and CCRR computations are shown in Tables 2 and 3 respectively.

Table 2 shows the total computational complexity for the traditional PTS and suggested method for B = 0.5, 1, 2. It shows the reduction in complexity for the suggested method compared to that of T-PTS with M = 128, 256, 512 and U = 2. For M = 512, the complexity is reduced by 9984, 8960 and 6912 for the proposed method with B = 0.5, 1, 2 compared to that of T-PTS scheme. For M = 256, the complexity is reduced by 4608, 4092 and 3072 respectively for the proposed method with B = 0.5, 1, 2 compared to that of T-PTS scheme. We observe that the complexity decreases as B decreases and lower complexity is obtained for lower values of B.

Table 3 shows the computational complexity reduction ratio for the suggested PTS technique for B = 0.5, 1, 2 for the number of subcarriers M = 128, 256 and 512. For CCRR calculations, we use the equation specified in (48). It is clear from Table 3 that CCRR improves as B decreases. For example for M = 256 and U = 2, CCRR values are 56.25%, 50% and 37.48% for proposed PTS scheme with B = 0.5, 1, 2. For M = 128 and U = 2, the CCRR values are 56.89%, 50% and 36.21% respectively for the proposed scheme with B = 0.5, 1, 2. CCRR percentage is improved for lower values of the tradeoff factor and CCRR percentage is lower for higher values of B.

7. Conclusion

A novel low complexity optimized PTS technique with RPSM for reducing PAPR in wireless OFDM systems is proposed in this paper. By applying the proposed technique, simultaneously PAPR reduction and computational complexity reduction are achieved compared to that of traditional PTS scheme. A favorable trade-off is obtained between reduction of PAPR and computational complexity by choosing the optimum value of the trade-off factor. PAPR reduces with the reduction in the number of subcarriers and increase in the number of subblocks. The analytical results closely matched with the simulation results. It is clear that our suggested PTS technique performs much better than traditional PTS technique in reduction of PAPR and computational complexity. The proposed technique improves the efficiency of the power amplifier and can be applied to the current wireless systems such as WiMAX and LTE.

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