Selective Tone Reservation method for PAPR reduction in SFBC-OFDM systems

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***Abstract*- The high Peak to Average Power Ratio (PAPR) of Orthogonal Frequency Division Multiplexing (OFDM) and MIMO-OFDM systems reduces the system efficiency. In this paper, an extension of Tone Reservation (TR) method is introduced for PAPR reduction in Space Frequency Block Coded OFDM (SFBC-OFDM) systems. The proposed algorithm is based on a time domain kernel which is added to the signal of the antenna with maximum PAPR to reduce its peak power. The time domain kernel has been designed such that the location of the reserved tones is compatible with the structure of the space frequency code. Simulation results show that the proposed method has a very close PAPR reduction performance to that of the well-known RC-PII(Reduced Complexity-Polyphase Interleaving and Inversion) method, but its complexity is much less than of RC-PII.**

***Index Terms*-** PAPR, MIMO-OFDM, Tone Reservation (TR), Alamouti code, SFBC.

I. INTRODUCTION

Orthogonal Frequency Division Multiplexing (OFDM) is an attractive technique for data transmission over wireless channels. OFDM scheme is a kind of multi carrier modulation where a block of the symbols is transmitted over N_C parallel sub channels. Thus, the frequency selective channel is converted to a set of frequency flat sub channels [1]. In OFDM scheme, the frequency separation between two adjacent sub channels is chosen at the minimum value in order to achieve the orthogonality of the subcarriers. Due to the overlap of the subcarriers in the frequency domain, OFDM systems have high spectrum efficiency [2].

The Multi Input-Multi Output (MIMO) is an effective technique which uses several transmitter and receiver antennas to take the advantages of Spatial Diversity (SD) or Spatial Multiplexing (SM) in modern wireless communication systems [3]. Two approaches are used in MIMO system. The first is spatial multiplexing which aims to increase the data rate and the second one is spatial diversity which

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aims to improve the bit error rate [4]. The combination of the OFDM with MIMO technique, named by MIMO-OFDM is a good candidate for future wireless communication systems [5]. The combination of spatial diversity with OFDM technique leads to SD-OFDM systems. Similarly SM-OFDM systems are the combination of spatial multiplexing and OFDM techniques. Two types of SD-OFDM system are defined: Space Frequency Block Coding OFDM (SFBC-OFDM) and Space Time Block Coding OFDM (STBC-OFDM). Similar to the case of single antenna OFDM systems, one of the major disadvantages of MIMO-OFDM system is high PAPR [6]. Several algorithms have been proposed for PAPR reduction of OFDM and MIMO-OFDM systems in the literature. Examples of these methods for single antenna OFDM are clipping and filtering [7], Tone Reservation (TR) [8], Active Constellation Extension (ACE) [9,23], Selected Mapping (SLM) [10], Partial Transmit Sequences (PTS) [11] and using codes with low PAPR [12]. Examples of techniques which are used for PAPR reduction of SM-OFDM systems are directed selected mapping (d-SLM) [13] and Spatial Shifting (SS) [14]. Several techniques have been introduced to reduce the PAPR of SFBC-OFDM systems such as Reduced complexity polyphase Interleaving and Inversion (RC-PII) [15], clipping technique [16], Selected Mapping (SLM) [17], Active Constellation Extension (ACE) [18] and Selective Tone Reservation (STR) [19] . Among these methods, RC-PII has a better performance but it needs Side Information (SI) to be transmitted to the receiver side.

In TR method, some of the subcarriers of the OFDM signal are used for PAPR reduction. In this paper TR method is applied to SFBC-OFDM system for PAPR reduction. The proposed algorithm is an extension of the method introduced in [8] for PAPR reduction of single antenna OFDM systems. In [8] a time domain kernel has been designed and it is shifted and added to OFDM signal to reduce the peak power. This process is done iteratively. The time domain kernel is determined by the location of the reserved tones. In [8] a time domain kernel with a low secondary peak has been designed. In SFBC-OFDM systems, the size of SFBC blocks applies a new limitation on the location of the reserved subcarriers. In this paper, based on this limitation a new time domain kernel has been designed for SFBC-OFDM systems. Based on this kernel, an iterative PAPR reduction algorithm has been proposed. In this method, the time domain kernel is added to the signal of the antenna with maximum PAPR. The performance and the computational complexity of the proposed method have been compared with those of RC-PII method.

The remainder of the paper is organized as follows: Section II describes the PAPR problem in MIMO-OFDM systems. Then, in section III the TR method is discussed. In section IV, the proposed iterative method for PAPR reduction of SFBC-OFDM systems is introduced. The performance of the proposed method is evaluated by simulation results in section V.

II. PAPR PROBLEM IN MIMO OFDM SYSTEM

In OFDM systems in each time interval of T seconds, N_C symbols are transmitted using N_C orthogonal subcarriers with frequency separation of $1/T$, where T is the symbol interval of OFDM signal. The vector of time domain samples of OFDM signal, denoted by $\mathbf{x} = [x(0), x(1), ..., x(N-1)]$ can be generated by the application of IFFT operation to the frequency domain vector $\mathbf{X} = [X(0), X(1), ..., X(N_C - 1)]$:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N_C-1} X(m) e^{j\frac{2\pi nm}{N}} \quad ; \; 0 \le n \le N-1 \tag{1}$$

Where, $X(m)$ is chosen from the constellation points and N/N_C is over sampling ratio. The PAPR of OFDM signal in dB is defined by

$$\text{PAPR}\{\mathbf{x}\} = 10 \log_{10} \left\{ \frac{\max\limits_{0 \le n \le N-1} |x(n)|^2}{E\left\{ |x(n)|^2 \right\}} \right\} \tag{2}$$

Where, $E\{.\}$ is the mathematical expectation. OFDM signals have larger PAPR than that of the single carrier signals. The high PAPR is a serious disadvantage of OFDM systems. In MIMO-OFDM systems, N_t transmitter antennas are used for transmission of OFDM signals. There are two main schemes in MIMO-OFDM systems. The first one is spatial multiplexing OFDM systems in which independent data blocks are transmitted from different antennas to increase the data rate by N_t times. In the second approach, called SD-OFDM, The transmitted blocks in different antennas are dependent. In SD-OFDM systems the goal is the improvement of bit error rate at the receiver side. If the channel response of the adjacent subcarriers can be assumed to be the same, then SFBC-OFDM system can be used to achieve the diversity. For example when $N_t = 2$, the OFDM symbols of two antennas are related by Alamouti scheme as shown below:

$$\mathbf{X}_1 = \left[X(0), -X^*(1), \ldots, X(2k), -X^*(2k+1), \ldots, X(N_c - 2), -X^*(N_c - 1) \right] \tag{3}$$

$$\mathbf{X}_2 = \left[X(1), X^*(0), \ldots, X(2k+1), X^*(2k), \ldots, X(N_c - 1), X^*(N_c - 2) \right]$$

Vectors $\mathbf{X}_1$ and $\mathbf{X}_2$ contain the frequency domain symbols transmitted from the first and second antennas, respectively. As can be seen from (3) the two symbols transmitted from two adjacent subcarriers of the second antenna are the permuted, conjugated and inverted version of the symbols of the first antenna. At the receiver side, this redundancy is used to improve the BER performance of the receiver. The time domain vectors containing the samples of the first and second antennas signals are denoted by x_1 and x_2 .They are obtained by the application of IFFT operation on frequency domain vectors $\mathbf{X}_1$ and $\mathbf{X}_2$, respectively. In this case, the PAPR is defined by the maximum PAPR value among all transmitter antennas:

$$\mathrm{PAPR}_{\mathrm{MIMO}} = \max_{\mathrm{i}=1,\ldots,\mathrm{N_t}} \left\{\mathrm{PAPR}\{\mathbf{x}_\mathrm{i}\}\right\} \tag{4}$$

where, $\mathrm{PAPR}\{\mathbf{x}_\mathrm{i}\}$ is the PAPR of the signal of the i*th* antenna.

III. TONE RESERVATION (TR) METHOD FOR PAPR REDUCTION

In TR algorithm, some tones in frequency domain are used to reduce the PAPR. These carriers are called Peak Reduction Carriers (PRCs). The index set of the PRCs is denoted by

$$\mathbf{Q} = [\mathrm{Q}(0), \mathrm{Q}(1), \ldots, \mathrm{Q}(\mathrm{R}-1)] \tag{5}$$

where, $\mathrm{R} < \mathrm{N_C}$ is the number of PRC symbols. The data vector and the symbols transmitted from PRC set in frequency domain are denoted by $\mathbf{X} = [\mathrm{X}(0), \mathrm{X}(1), \ldots, \mathrm{X}(\mathrm{N_C}-1)]$ and $\mathbf{C} = [\mathrm{C}(0), \mathrm{C}(1), \ldots, \mathrm{C}(\mathrm{N_C}-1)]$, respectively. It is clear that

$$\mathrm{X}(\mathrm{m}) = 0\,;\, \mathrm{m} \in \mathbf{Q} \quad , \quad \mathrm{C}(\mathrm{m}) = 0\,;\, \mathrm{m} \in \mathbf{Q}^{\mathrm{c}} \tag{6}$$

where, $\mathbf{Q}^{\mathrm{c}}$ is the complement set of $\mathbf{Q}$. The symbols of the OFDM block are

$$\mathrm{Z}(\mathrm{m}) = \mathrm{X}(\mathrm{m}) + \mathrm{C}(\mathrm{m}) = \begin{cases} \mathrm{X}(\mathrm{m}) & ;\mathrm{m} \in \mathrm{Q}^{\mathrm{c}} \\ \mathrm{C}(\mathrm{m}) & ;\mathrm{m} \in \mathrm{Q} \end{cases} \tag{7}$$

The time domain signal is

$$\mathbf{z} = \mathrm{IFFT}\{\mathbf{X}+\mathbf{C}\} = \mathrm{IFFT}\{\mathbf{X}\}+\mathrm{IFFT}\{\mathbf{C}\} \\ = \mathbf{x}+\mathbf{c} \tag{8}$$

The signal $\mathbf{z}$ has lower PAPR value than that of $\mathbf{x} = \mathrm{IFFT}\{\mathbf{X}\}$. The PAPR of the overall signal is:

$$\mathrm{PAPR}\{\mathbf{z}\} = \frac{\max\limits_{0\le n\le N-1} |x(n)+c(n)|^2}{\frac{1}{N}\sum_{n=0}^{N-1}|x(n)|^2} \tag{9}$$

In [8], an iterative method has been introduced for the generation of the time domain signal $\mathbf{c} = \mathrm{IFFT}\{\mathbf{C}\}$. Assume $\mathbf{K} = [K(0), K(1), ..., K(N_C-1)]$ is a frequency domain kernel with {0, 1} elements where

$$K(m) = \begin{cases} 1 & ; m \in \mathbf{Q} \\ 0 & ; m \in \mathbf{Q}^c \end{cases} \tag{10}$$

The time domain kernel $\mathbf{k} = \mathrm{IFFT}\{\mathbf{K}\}$ has a maximum peak at $k(0)$. In each iteration, the peak value of the time domain kernel is shifted to the peak position of the signal $\mathbf{z}$ and it is scaled to decrease the peak value of $\mathbf{z}$.

$$\mathbf{c}^{l-1} = \mathbf{c}^{l} + \alpha^{l}\Gamma^{t^{l}}\{\mathbf{k}\} \tag{11}$$

where, $\mathbf{c}^{\ell}$ represents the time domain OFDM signal after the ℓth iteration, t^{ℓ} is the index of peak position in the ℓth iteration, α is complex scaling factor and Γ^{n} denotes n units, circular right shift function. The parameters t^{ℓ} and α^{ℓ} are found by

$$t^{l} = \arg\max_{0\le n\le N-1}|z^{l-1}(n)|^2 \tag{12}$$

$$\left|z^{l-1}(t^{l}) + \alpha^{l}k(0)\right| = \zeta \tag{13}$$

where, ζ is the threshold level that its optimum value will be determined by the simulation. In each iteration, only one peak value is decreased and after l iterations we have:

$$\mathbf{z}^{\ell} = \mathbf{x} + \mathbf{c}^{\ell} \tag{14}$$

The main problem in TR method is the selection of PRC set. In [8] it has been proposed that the PRC set, $\mathbf{Q}$, is selected such that the second peak of $k(n)$ is minimized, i.e.

$$\mathbf{Q}_{opt} = \arg\min_{Q} \left\| |k(1)|, |k(2)|, \ldots, |k(N-1)| \right\|_{\infty} \tag{15}$$

where $\|.\|_{\infty}$ denotes the maximum value, this problem is NP-hard and searching over all possible sets is very complex. As an example for $N_C = 64$ and the number of PRCs =8, we have $\binom{64}{8} = 4.4262 \times 10^9$ possible candidates for PRC sets. In [8] a sub optimal method has been introduced that is based on minimization of the variance of time domain kernel. As shown in [8], the set of time domain kernels with minimum secondary peak contains the set of the time domain kernels that have lower variance in comparison to others.

IV. PROPOSED ALGORITHM FOR SFBC-OFDM SYSTEM

In SFBC-OFDM systems with two transmit antennas and Alamouti code, the number of data subcarriers between two adjacent PRCs must be even, because the blocks of Alamouti code have the length of 2. Otherwise, Alamouti code cannot be applied to the adjacent subcarriers. Fig. 1 illustrates the above limitation for selecting the reserved carriers. In Fig. 1, the dark cells represent the reserved tones in frequency domain vector. In this situation, the total number of possible PRCs that meet the above limitation is less than that of single antenna OFDM systems. To find the total number of valid PRC sets with considering Alamouti block code limitation, the number of possible positions of R "1"s (location of PRCs) among $N_C - R$ "0" samples (location of data symbols) should be calculated, simply it can be seen that each "1" has $\left((N_C - R)/2\right) + 1$ possible position individually, so the total number of possible PRC sets is

$$\frac{\left\{\left((N_C - R)/2\right) + 1\right\}^R}{R!} \tag{16}$$

As an example, for $N_C = 64$ and the number of PRCs =8, the answer is 1.2407×10^7 . It can be seen that the limitation of SFBC leads to a considerable reduction in the number of candidate PRC sets.

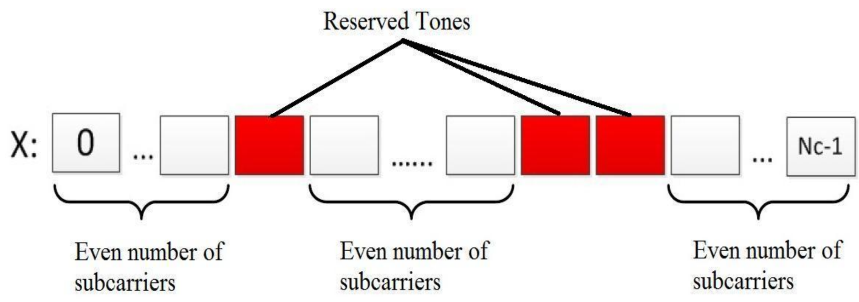

Fig.1. Limitation for position of reserved tones in SFBC-OFDM data block

Similar to the case of single antenna OFDM system, the main problem in this method is the selection of PRC set. Because of the high complexity of searching among all possible PRC sets, in practice about 10^7 sets are generated randomly and the variance of the time domain kernel is calculated, then about 10 percent of the PRC sets which have lower variance values than that of the others are selected and finally the best PRC set is selected by the calculation of the secondary peak of time domain kernel. In SD-OFDM system, to find a valid PRC set for SFBC-OFDM with Alamouti block code it is proposed to generate the random PRC sets by the algorithm which has been shown in Fig. 2. In this algorithm, there are R ones and in each step even number of zeros is inserted between two consecutive ones. The location and the number of inserted zeros are randomly generated.

For $N = 64$ and $R = 8$, 10^7 random PRC sets were generated and 10% of the sets with minimum variance of the time domain kernel were selected. Among the selected sets, the set with minimum second peak was chosen. The locations of PRCs are $\mathbf{Q} = \{1, 6, 13, 20, 21, 24, 37, 46\}$. Fig. 4 illustrates the time domain kernel generated from the selected PRC set. In this figure, the time domain kernel of the PRC set introduced in [8] also has been plotted (without SFBC limitation). As can be seen form this figure, these two kernels have the same values of the secondary peak. Thus, the SFBC limitation does not affect the performance of TR method.

The PAPR of multiple antenna systems is defined by the maximum value of the PAPRs of different antennas. Thus, it is proposed that the time domain kernel is added to the signal of the antenna with maximum PAPR. This approach is called selective-TR, because in each iteration the antenna with maximum PAPR is selected and its signal is updated.

$$\text{Inputs: } \left| \begin{array}{l} N_C \leftarrow \text{Number of subcarriers} \\ R \quad \leftarrow \text{Number of reserved tones} \end{array} \right.$$

$$\text{Output: } \mathbf{P} \leftarrow \text{Frequency domain vector}$$

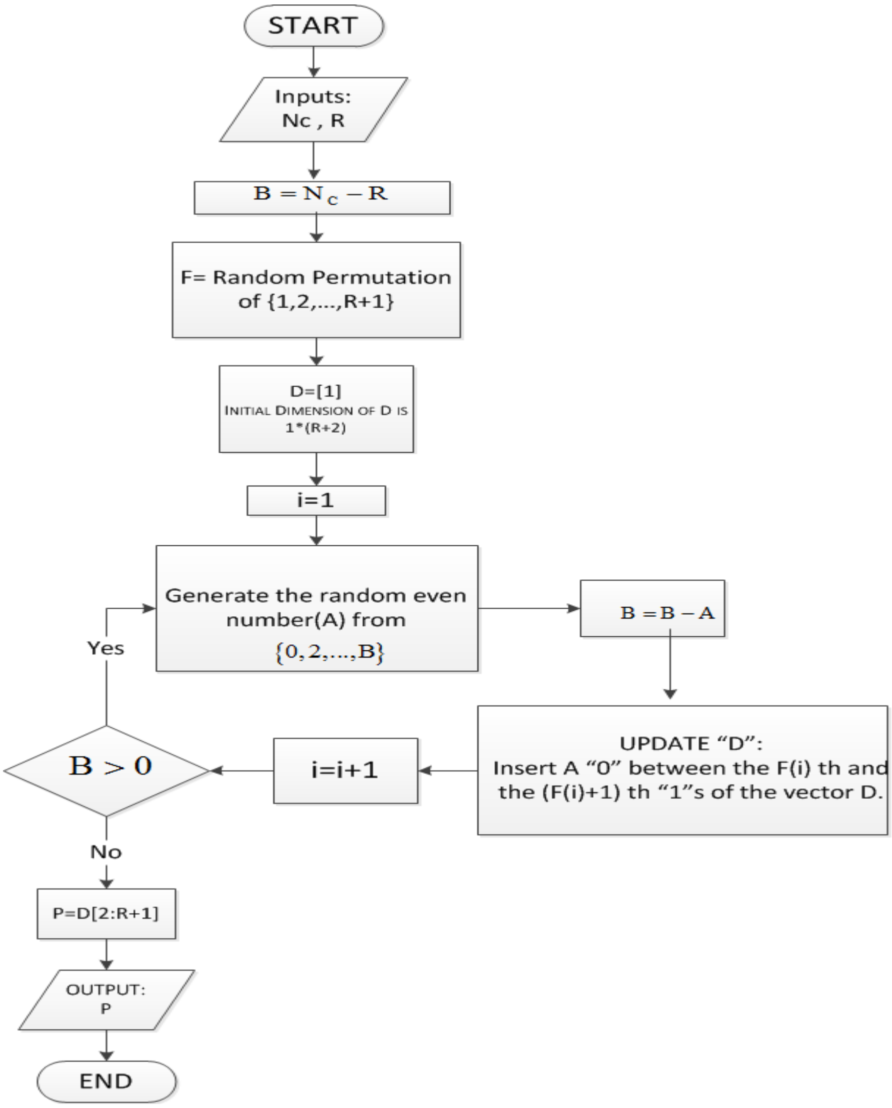

Fig.2. The proposed algorithm for generation of the random PRC sets with SFBC limitation

V. SIMULATION RESULTS

SFBC-OFDM system with two transmitter antennas and 64 subcarriers with 8 PRCs have been simulated. Selective TR method has been applied for PAPR reduction. The data symbols are chosen from the 16-QAM constellation points. The PRC set is chosen as mentioned in previous section.

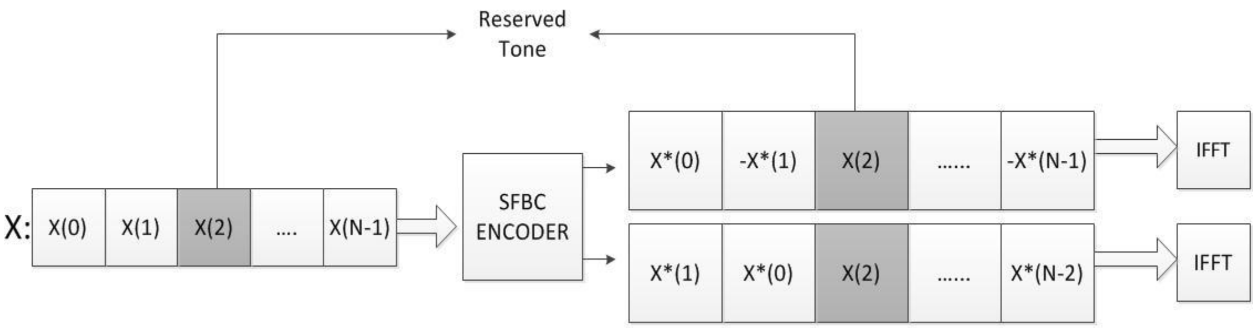

Fig.3. Selected tones for peak reduction signal in SFBC-OFDM system

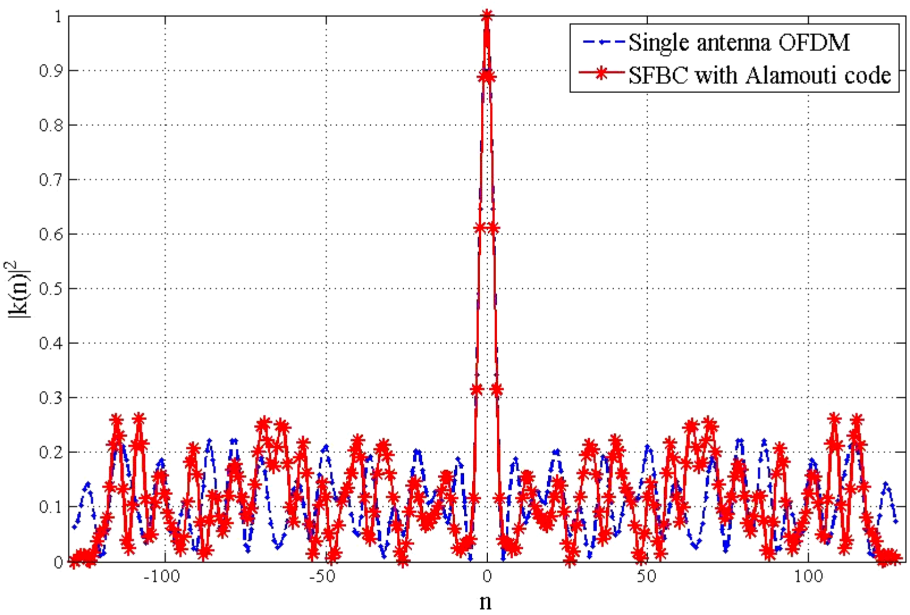

Fig.4. Time domain kernel in TR method for $\mathbf{N_c = 64}$ and R=8 for single antenna and SFBC-OFDM system

In TR method, the value of threshold level (ζ) should be optimized by simulation. Fig. 5 shows the average of the PAPR versus the parameter ζ (normalized by the average power) for different number of iterations. As can be seen, the optimum value of ζ is about 5.4dB above the average power.

Fig. 6 represents the PAPR reduction performance of the Selective TR algorithm for SFBC-OFDM system with Alamouti block codes. The performance of the proposed method has been compared with the RC-PII method. In RC-PII algorithm, the frequency domain vectors $\mathbf{X}_{\text{ant}}\ ;\text{ant}=1,2$ are partitioned into M disjoint sub blocks that each of them are zero padded such that the length of each subblock is as that of the original OFDM block. None zero subcarriers in each block must have Alamouti code structure. By the inversion (multiplication by "-1") and interleaving (change the position of even and odd symbols), different representations of input OFDM blocks can be generated. The representation with minimum PAPR is selected and it is transmitted with side information (the index of selected representation). In RC-PII method

$$(2M-1)N_t N + (NN_t (2M-1)\log_2(N_C/M))/2 \tag{17}$$

additional Complex Multiplications (CM) and

$$N_t MN + NN_t (2M-1)\log_2(N_C/M) \tag{18}$$

additional Complex Additions (CA) are used. The n_iter iterations of the proposed selective TR method consist of $N\times(n\_iter)$ complex multiplications and $N\times(n\_iter)$ complex additions. Table I compares the complexity of the proposed method for different number of iterations and RC-PII method with different values of the parameter M.

As can be seen form Fig. 6, the performances of the proposed algorithm with $n\_iter=5$ and RC-PII method with $M=4$ are approximately the same but TABLE I shows that the complexity of RC-PII with $M=4$ is about ten times more than that of the proposed method. It is noteworthy that unlike RC-PII method, the proposed method does not need side information.

To evaluate the effectiveness of the optimized PRC set, Selective-TR method was applied to SFBC-OFDM system with uniform PRT set, **Q**= {1,10,19,28,37,46,55,64}. Comparison of the Figures 6 and 7 shows that the performance of selective TR method has a considerable degradation when uniform PRC set is used.

VI. CONCLUSION

This paper presents a selective TR method with a modified PRC set for PAPR reduction of SFBC-OFDM system. A time domain kernel is generated from the PRC set and the scaled and shifted version of the time domain kernel is added to the signal of the antenna with maximum PAPR in each iteration. The time domain kernel is determined such that the SFBC coding can be applied to the adjacent subcarriers. Simulation results show that the proposed method achieve the same performance as that of the well-known RC-PII method with lower computation complexity.

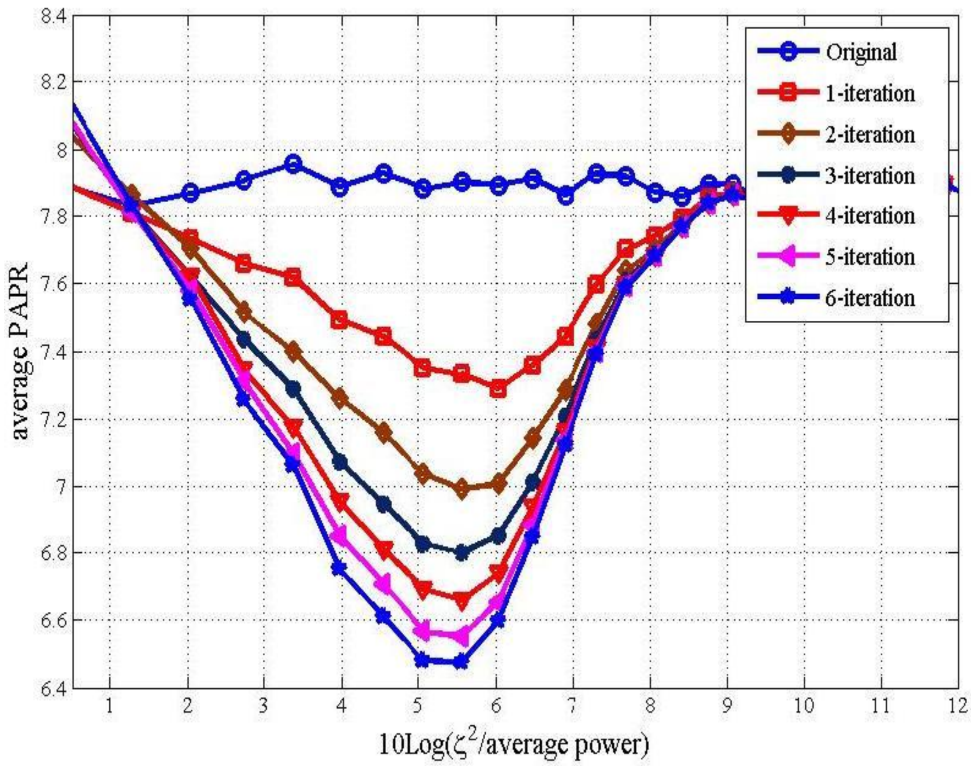

Fig.5. Average PAPR value for different values of ζ in TR method with in SFBC-OFDM system with two transmitter antennas and $\mathbf{N_c = 64}$.

TABLE I
NUMBER OF COMPLEX MULTIPLICATIONS (CM) AND ADDITIONS (CA) FOR RC-PII AND SELECTIVE TR METHODS IN SFBC MIMO-OFDM SYSTEM WITH 64 SUBCARRIERS

Selective TR			**RC-PII**		
n_iter	**CM**	**CA**	**M**	**CM**	**CA**
2	512	512	4	10752	16384
4	1024	1024	8	19200	27136
5	1280	1280	16	31744	39936

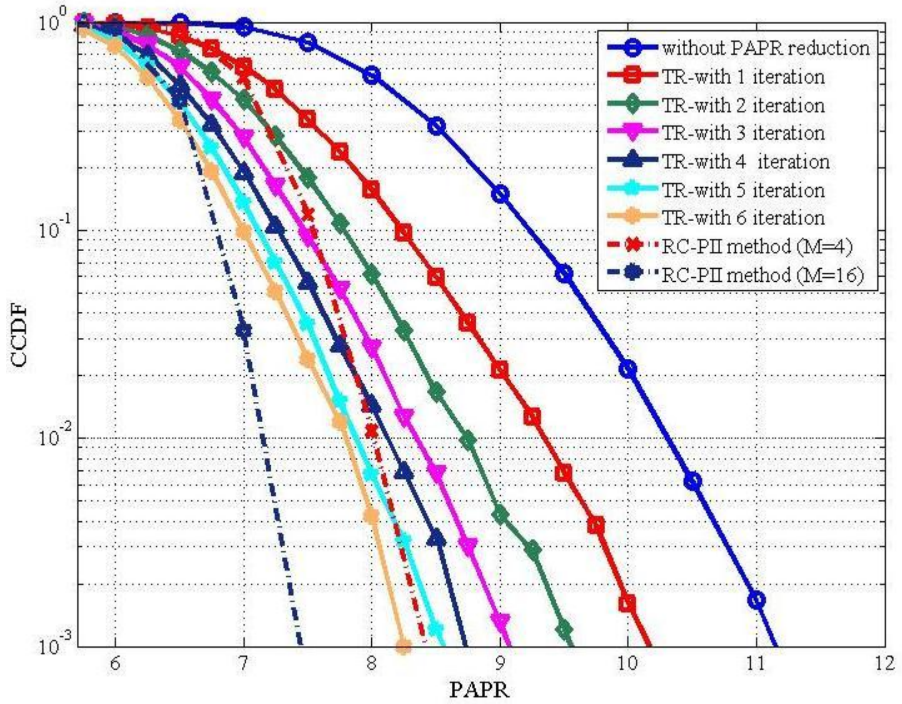

Fig.6. Performance of the proposed Selective TR algorithm (with optimized PRT set) in comparison to that of the RC-PII method for a SFBC –OFDM system with two transmitter antennas and $\mathbf{N_c = 64}$

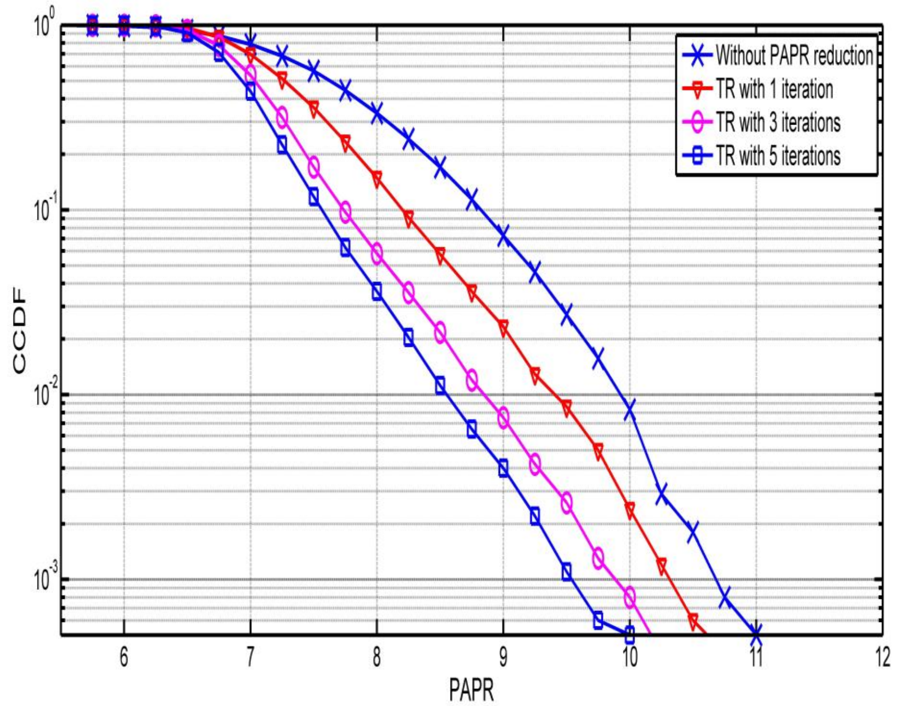

Fig.7. Performance of the Selective TR algorithm with uniform peak reduction tones for SFBC –OFDM system with two transmitter antennas and $\mathbf{N_c = 64}$

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