# *PAPR Reduction of OFDM Signals using Active Constellation Extension and Tone Reservation Hybrid Scheme*

Eugen-Victor Cuteanu
Communication Department
Politehnica University, Faculty of Electronics and Telecommunications
Timisoara, Romania
victor.cuteanu@gmail.com

Alexandru Isar
Communication Department
Politehnica University, Faculty of Electronics and Telecommunications
Timisoara, Romania
alexandru.isar@etc.upt.ro

*Abstract*—**The Orthogonal Frequency Division Multiplexing is one of the widely used modulation techniques in the present broadband wireless technology. The opportunities and challenges of this modulation technique are derived from its native advantages and disadvantages. One of the main problems is the high peak-to-average power ratio of transmission signal due to the superposition of many subcarriers. This paper presents a new hybrid peak-to-average power ratio reduction technique, which combines an active constellation extension method with a tone reservation method. The paper presents the performance and advantages of the mixed technique and compares it with other existing methods. The simulations shown that the proposed technique realizes an increased peak-to-average power ratio reduction compared to component methods with similar parameters.**

***Keywords-OFDM; PAPR; Active Constellation Extension; Tone Reservation***

## I. INTRODUCTION

The Orthogonal Frequency Division Multiplexing (OFDM) is one of the most efficient and popular modulation techniques used in broadband wireless communication systems like Worldwide Interoperability for Microwave Access (WiMAX), Terrestrial Digital Video Broadcast (DVB-T), or wireline systems like Asymmetric Digital Subscriber Line (ADSL). One of the main practical issues of the OFDM is the Peak-to-Average Power Ratio (PAPR) of the transmitted signal. This high PAPR occurs because of the time-domain superposition of the many data subcarriers which compose the OFDM signal. Due to the large number of subcarriers, the resulting time-domain signal exhibits Rayleigh-like characteristics and large time-domain amplitude variations. These large signal peaks require the high power amplifiers (HPA) to support wide linear dynamic range.

Higher signal level causes non-linear distortions leading to an inefficient operation of HPA causing intermodulation products resulting unwanted out-of-band power. In order to reduce the PAPR of OFDM signals, many solutions have been proposed and analyzed. The efficiency of these methods can be evaluated considering their characteristics of non-linearity, amount of processing and size of side information needed to be sent to receiver.

The class of linear methods is represented by approaches like partial transmit sequence (PTS) [2], selective mapping (SLM) [1], and tone reservation (TR) [5].

In the SLM method, based on a set of predefined phase arrays, several vector rotations of the original frequency domain OFDM signal are performed. For each variant obtained by rotations, the corresponding PAPR is evaluated. The variant with the lowest PAPR is chosen for the transmission.

A similar approach is applied in case of PTS method, where the *N* complex values representing the OFDM signal symbols are grouped into *K* sub-blocks of *N*/*K* symbols. The case of blocks with contiguous carriers has the advantage of simplicity and it is more suitable for detection systems. The case of non-contiguous carrier blocks offers better peak factor (PF) reduction capability at the cost of extra complexity. The method generates a set of signal derivates by rotating the symbols from each block with one phase from a given set of *K* phases with values from a given finite set. Then, after calculation of the corresponding PAPR of each signal variant, the one with minimal PAPR is chosen for the transmission.

Both methods provide efficient PAPR reduction, having the drawback of additional side information required to be sent to receiver. Another disadvantage of these methods is that the complexity of computation is increasing with the number of phase set and block number.

Optimizations of these methods have been proposed in several papers [3][4].

Another PAPR reduction method is tone reservation (TR), which uses a set of reserved set of subcarriers (tones) to generate signals with lower PAPR level. Besides the advantage of no additional distortion, this method also doesn’t need to transmit additional information to the receiver. Because not all subcarriers are used to transmit useful information, this method is considered to lower the data rate of the OFDM-based systems.

Since the development of the original tone reservation method, in order to reduce the computation complexity and to improve the performance, several derivate techniques have been proposed: selective mapping of partial tones (SMOPT) [6], One-Tone One-Peak (OTOP) [7] and one-by-one iteration [8].

Another optimized variant of this method proposes to generate tones for the K largest peaks of the signal. The phases of these tones are chosen to be opposite to $\varphi_j+n\pi/2$, where $\varphi_j$ is the phase of the identified peaks, $j=1, 2, \ldots, K$ and $n=0, 1, 2, 3$. The procedure is iterated until convergence reaches the expected threshold [5].

The class of non-linear methods is represented by approaches like active constellation extension (ACE), clipping, partial clipping, and signal compression.

The ACE method change the original OFDM signal by modifying amplitude and phase of tones whose base band modulation symbol is an outer point of the constellation. Those outer signaling points of the conventional constellation are dynamically moved toward outside of the original constellation in order to reduce the PAPR level of the transmitted signal. The domain for allowed alternative points is chosen so that the signal processing does not reduce the constellation's minimum-distance but lowers the PAPR level [15][17].

For additional PAPR reduction, some proposed derivate methods consider outers points projection onto squares or circles around all the QAM constellation points and intentional distortion within the allowed bounds. The tradeoff between level of the constellation distortion and PAPR level is analyzed and optimized as well [16].

The clipping method is another well known non-linear PAPR reduction technique, where the amplitude of the signal is limited to a given threshold. Taking in consideration the fact that the signal must be interpolated before A/D conversion, a variety of clipping methods has been proposed. Some methods suggest the clipping before interpolation, having the disadvantage of the peaks regrowth. Other methods suggest the clipping after interpolation, having the disadvantage of out-of-band power production. In order to overcome this problem different filtering techniques have been proposed. Filtering can also cause peak regrowth, but less than the clipping before interpolation [9].

Another clipping technique supposes that only subcarriers having the highest phase difference between the original signal and its clipped variant will be changed. This is the case of the partial clipping (PC) method [10].

For additional PAPR reduction, some papers proposed µ-law/A-law companding functions [13], exponential companding function [12], piecewise-scales [11] or polynomial ratio functions [14] after the clipping.

The rest of the paper is organized as follows. The second section describes the OFDM signal, some of its properties, and some aspects of the high power amplifier. The third section describes the proposed hybrid PAPR reduction scheme. In the fourth section is described the clipping method as PAPR reduction method of reference. Next, the numerical results highlighted by the computer simulation are presented and discussed in the fifth section. Based on the obtained results, some conclusions are presented in the sixth section.

## II. THE OFDM SIGNAL

In an OFDM-based system, the signal samples are grouped in blocks of N symbols, $\{X_n, n=0,1,\ldots,N-1\}$, which are modulating a set of N subcarriers, with frequencies $\{f_n, n=0,1,\ldots,N-1\}$. These subcarriers are chosen to be orthogonal, that is $f_n=n\Delta f$, where $\Delta f=1/T$, and $T$ is the OFDM symbol period. The resulting signal can be written as:

$$x(t)=\frac{1}{\sqrt{N}}\sum_{n=0}^{N-1}X_n e^{j2\pi f_n t}\ . \tag{1}$$

In order to avoid the intersymbol interference (ISI) generated by the multipath channels, each signal period is extended with a fraction from itself, corresponding to a guard interval. After Digital-to-Analogue (D/A) conversion, the signal is applied to the modulator. Next, the resulted signal is applied to a high-power amplifier (HPA) which drives the antenna load.

At the receiver, after demodulation, the guard will be removed, the symbols being evaluated for a time interval of $[0,T]$.

Time domain samples of the low-pass OFDM signals in the complex domain are appreciatively Gaussian distributed due to statistical independence of subcarriers. Due to this fact, sporadically, the signal presents peaks, which cause the PAPR problem. The expression of the PAPR for a given OFDM signal block is given by:

$$PAPR(x)=\frac{\max\left(\left|x(t)\right|^2\right)}{E\left[\left|x(t)\right|^2\right]}, \tag{2}$$

where $E[.]$ denotes the expectation operator.
This is usually evaluated using the complementary cumulative distribution function (CCDF) of the PAPR:

$$\begin{aligned} CCDF(Y) &= \Pr(PAPR>Y)= \\ &=1-\Pr(PAPR<Y) \end{aligned} \tag{3}$$

where $Y$ is a PAPR threshold.

Another quality measure refers to the non-linearity of the transmitted signal which is produced by the HPA. This is the Signal-to-Distortion Ratio (SDR) defined as:

$$SDR=\frac{\left\|x\right\|^2}{\left\|x-g(x)\right\|^2}, \tag{4}$$

where $g(.)$ is the memoryless nonlinearity representing the effects of the HPA.

In order to describe these effects, several models have been proposed. One of the well known models is the Saleh Model, which is described by the following input-output equations:

$$A_{HPA}(u) = \frac{\alpha \cdot u}{1+\beta \cdot u^2}, \qquad (5)$$

$$P_{HPA}(u) = \frac{\alpha \cdot u^2}{1+\beta \cdot u^2}, \qquad (6)$$

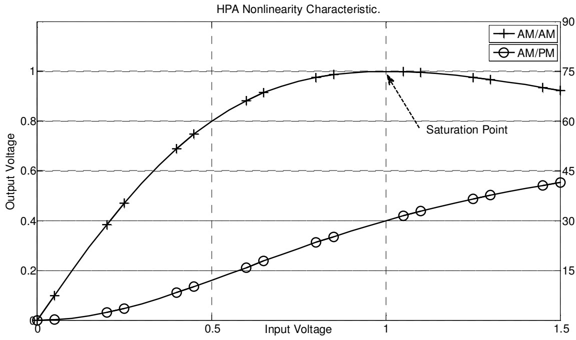

Figure 1. Example of a HPA nonlinear characteristic. Amplitude and phase transfer functions are presented.

where $A(u)$ is the amplitude characteristic and $P(u)$ is the phase characteristic.

An example for the coefficients with the values of α=2 and β=1, is presented in Figure 1.

The optimal solution for PAPR problem may not be the best solution for the SDR problem and vice versa. Because these two problems are correlated, in practice a suboptimal solution may be chosen [15].

## III. THE HYBRID METHOD

The proposed hybrid PAPR reduction technique is obtained by serialization of active constellation extension method and sequential tone reservation method.

The main idea for combining the two methods is relying on the observation that the cumulative signal processing for PAPR reduction will increase the overall performance. Furthermore, the idea is based on the fact that each of the considered methods is based on a different principle. One performs a controlled signal distortion and the other realizes different changes of the non-data subcarriers.

The block diagram of the proposed method is presented in Figure 2. The performance of the proposed PAPR reduction technique is analyzed with a MATLAB simulator as presented in Figure 3. Within this simulator, the samples from the generated signal are mapped from binary representation to the M-QAM or M-PSK constellation points. The obtained complex values are grouped in blocks of $N$ elements each, forming the OFDM symbols.

The obtained OFDM frames are applied to the PAPR reduction blocks. For a better performance comparison, besides the proposed ACE-TR method, additionally the clipping method [9] is taken into consideration.

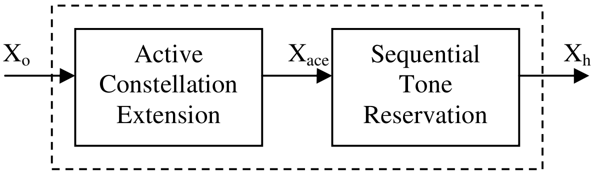

Figure 2. The Hybrid ACE-TR scheme for PAPR reduction.

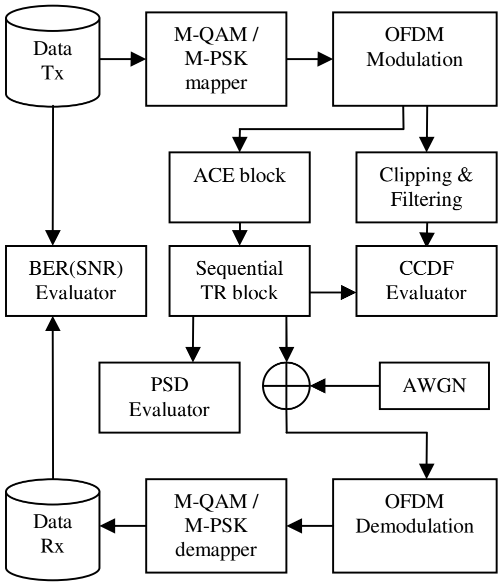

Figure 3. MATLAB model for the analysis of the hybrid PAPR reduction technique.

The PAPR reduction blocks alter the original signal. Due to this fact, for evaluation of communication's performance and efficiency, the simulator estimates the bit error rate (BER) and power spectral density (PSD) for the signal obtained after processing for PAPR reduction.

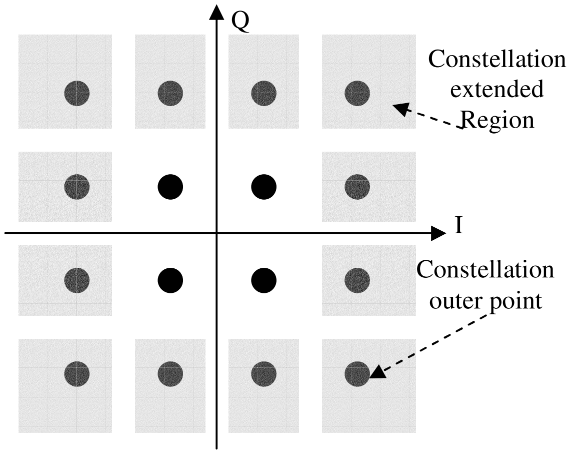

Figure 4. Example of an extended constellation. The original points and allowed extended domain for outer points for 16-QAM are indicated.

The ACE method requires both time-domain and frequency-domain signal processing. As already mentioned, the main idea of this method is to shift the outer constellation points toward exterior of original constellation generating an alternative representation of the same symbol. The allowed domains for these outer points are presented in Figure 4, when 16-QAM is used as base band modulation.

The boundaries of these domains are constrained by the constellation's minimum-distance. The reason for this limitation is to prevent a decrease of BER performance at the receiver.

In the present work, the ACE was implemented according with the following algorithm [15]:

1) Starting with a block of $N$ data symbols $X_o$, representing a frequency domain OFDM frame;

2) Apply IFFT to get the corresponding time-domain signal representation $x[n]$.

3) Clip any sample which satisfies the condition: $|x[n]| \geq A$, to obtain a signal with reduced maximal amplitude modulus:

$$\tilde{x}[n] = \begin{cases} x[n], & |x[n]| \leq A \\ A \cdot e^{j\theta[n]}, & |x[n]| \geq A \end{cases}, \tag{7}$$

where

$$x[n] = |x[n]| \cdot e^{j\theta[n]}, \tag{8}$$

4) Apply FFT to obtain the frequency-domain representation $\tilde{X}$ of the previous time-domain clipped signal $\tilde{x}$ ;

5) Enforce all ACE constraints on $\tilde{X}$ by restoring the original values for all inner points and limit the values for all outer points to reside within their corresponding extended domains as already mentioned;

6) Return to step 2 and iterate the algorithm until the maximum number of iterations is reached or the PAPR level decreased until a given threshold.

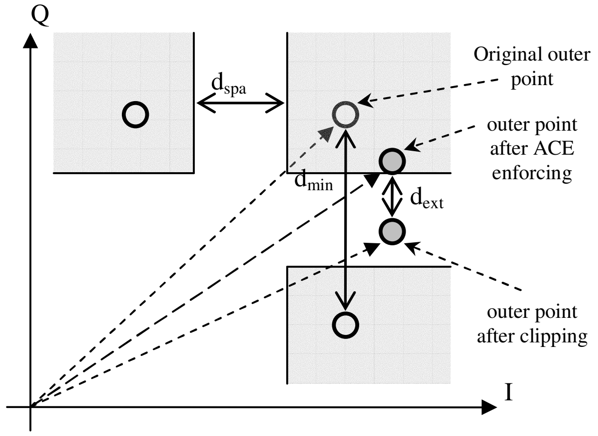

Figure 5. ACE outer point enforcing. Exemplification for 16-QAM.

In order to apply the ACE constraints for the outer points of the constellation, their corresponding vectors must be changed. Depending on their relative location versus the location of the original point and on the allowed extended domain, the algorithm may change vector's amplitude or phase or both.

A solution would be to rotate the vector until the outer point enters back into corresponding extended domain. When this operation is not enough, the vector's amplitude can be increased accordingly.

In the present work, in order to reduce the computation complexity, the ACE constraints are applied by checking and changing the Cartesian coordinates separately. The present algorithm considers the constellation's minimum-distance $d_{min}$, the distance between two adjacent extended domains $d_{spa}$, the coordinate of the original outer point, and the coordinate of the actual point obtained after clipping. When the in-phase or quadrature value is under the threshold indicated by the corresponding domain border, the difference $d_{ext}$ is added to shift the point back into its domain. This approach is presented in Figure 5. For the case of the M-PSK modulation, the ACE constraint is applied using a similar approach. The difference is that for the M-PSK case, all constellation points can be used to lower the PAPR, and their corresponding extended domains are represented by radial sectors with the angular size of $2\pi/M$ radians.

Next, the obtained frequency-domain signal is applied to the tone reservation method, which is presented in Figure 6. It selects $T$ pilot tones positions from a complete set of $Q$ no-data carrier positions and a set of $M$ complex values, forming a set of $M^T$ possible combinations.

This search space may lead to an increased amount of data computation. The chosen tone reservation algorithm decreases the computation complexity by attempting a reduced search space by trying all $M$ values on the first pilot P[0], while the other pilots, P[1],…,P[$T$-1], have a "randomized" or zero initial state. Once an optimal value is found, a similar procedure is repeated on the other pilot positions. For further computation complexity reduction, the time-domain signals equivalent for all pilot tones can be computed and stored initially into memory. In this case, more operations are done in time-domain, fact which determines a decreased number of FFT operations [5].

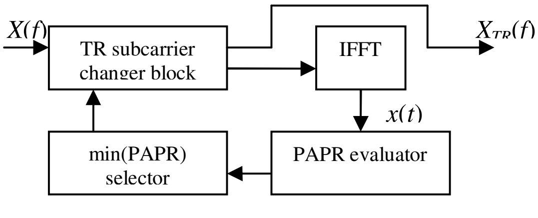

Figure 6. Sequential Tone Reservation method.

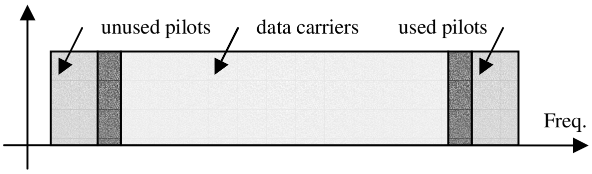

Figure 7. Allocation of reserved tones within an OFDM symbol. (symmetrical) – Type I

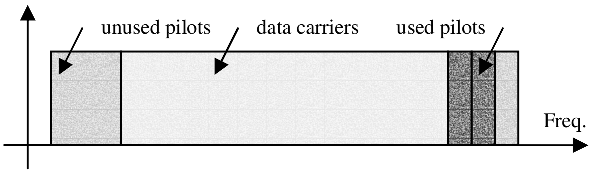

Figure 8. Allocation of reserved tones within an OFDM symbol (lateral, inner) – Type II

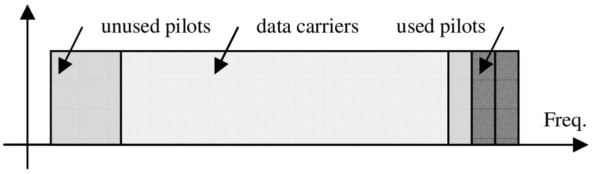

Figure 9. Allocation of reserved tones within an OFDM symbol (lateral, outer) – Type III

Because the TR method operates on some subcarriers from the frequency-domain signal, the displacement of these non-data subcarriers may impact the method's performance. Depending by position, the allocation of the reserved subcarriers may be symmetrical or lateral occupying the lower or higher part of the signal's spectrum. The considered variants are presented in Figures 7 and 8.

When the TR block follows after the ACE block, as Figure 2 indicates, the interfacing of these blocks has to be properly adapted.

Both PAPR reduction blocks have to operate on the same signal. Therefore, in order to have same frequency spectrum, the non-data subcarriers used within TR block has to be available at the ACE block's input.

The ACE block performs a nonlinear signal processing, which will affect the non-data subcarriers as well. Because these subcarriers are not carrying any information, they have no ACE constraints as method requires for the constellation points of the data subcarriers. From the ACE perspective these non-data subcarriers have the optimal value for lowering PAPR.

Contrary, the TR block will change the values of these non-data subcarriers in order to search an OFDM alternative signal with a decreased PAPR. Because some of these subcarriers will provide no improvement from the PAPR reduction point of view, the initial value set of the ACE block has to be considered.

In order to make the proper adaptation, the TR constellation point set of each non-data subcarrier has to include the initial value obtained after previous signal processing performed by the ACE block.

## IV. THE CLIPPING METHOD

For analysis of the efficiency of the proposed hybrid technique, also a pure nonlinear method has been considered. This is the clipping method with frequency-domain filtering as presented in [9]. The block diagram of this method is presented in Figure 10. It consists in a zero padding block, an IFFT block, an effective clipping block, and a frequency domain block. For a frequency-domain input signal represented by a vector $A_{\text{in}}$ with $N$ elements $[a_0,\ldots,a_{N-1}]$ and an oversampling factor $p$, the zero padding inserts $N(p-1)$ zeros in the middle of this vector, forming the new vector $A_{\text{zp}}$. The clipping block limits the amplitude of the time-domain signal to a given threshold. The resulted signal $a_{clp}$ is then applied to the frequency domain filter where the output signal $a_{out}$ is obtained.

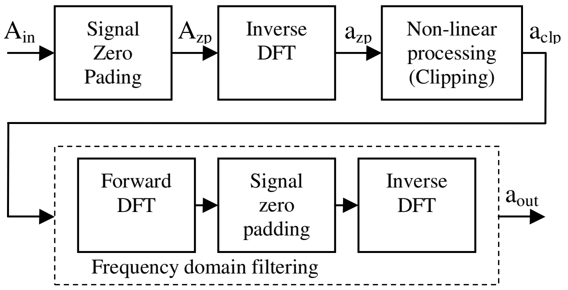

Figure 10. Clipping with filtering PAPR reduction method.

The clipping ratio ($CR$) applied in this method is defined as ratio of the clipping level $A$ to the root-mean-square power $\sigma$ of the unclipped baseband signal,

$$CR = 20 \cdot \log_{10}\left(\frac{A}{\sigma}\right). \tag{9}$$

The filtering block is composed by an FFT block, another zero padding block and an IFFT block. It is designated to reduce the out-of-band noise without distorting the in-band discrete signal.

## V. NUMERICAL RESULTS

The MATLAB simulations have been performed for base-band signals with $N$=128 subcarriers using M-QAM and M-PSK modulations. The frequency-domain signal is extended with additional $Q$=24 no-data subcarriers. From this set, $T$=12 subcarriers are used for PAPR reduction by the TR method. The corresponding constellation consists in sets of $M$=16 points. For the reference clipping method, the simulation considers the clipping rate $CR$ having some values in the range of 6-14 and the oversampling factor $p$ set to 2.

For the OFDM signal spectrum computation, it was considered that the distance between two adjacent subcarriers is 0.2 MHz.

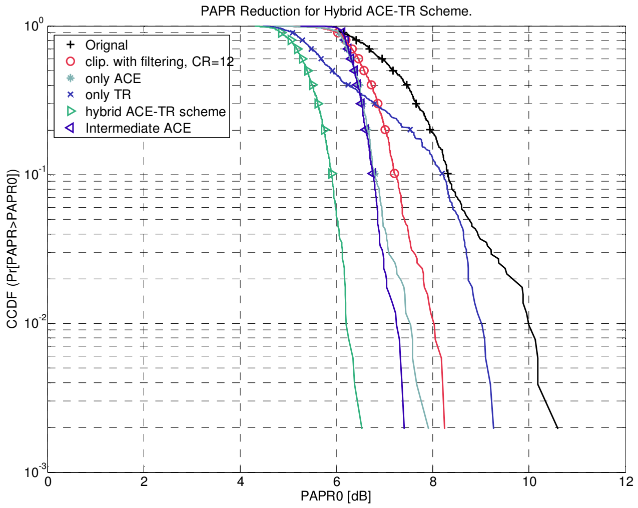

Figure 11. PAPR reduction using hybrid ACE-TR method. Type I

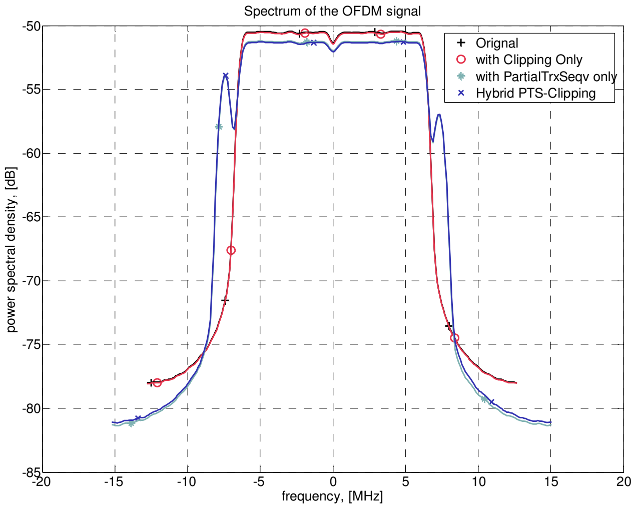

Figure 14. Spectr. of OFDM signal before/after PAPR reduction. Type I

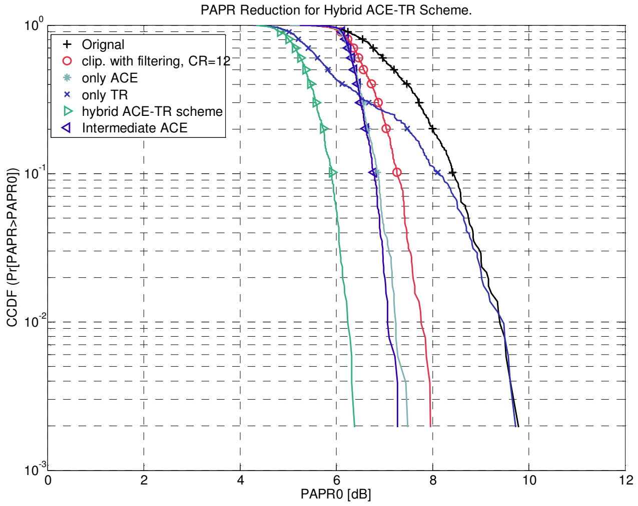

Figure 12. PAPR reduction using hybrid ACE-TR method. Type II

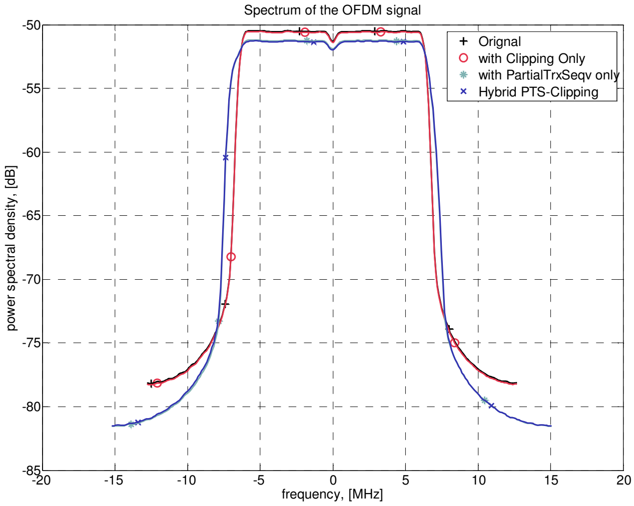

Figure 15. Spectr. of OFDM signal before/after PAPR reduction. Type II

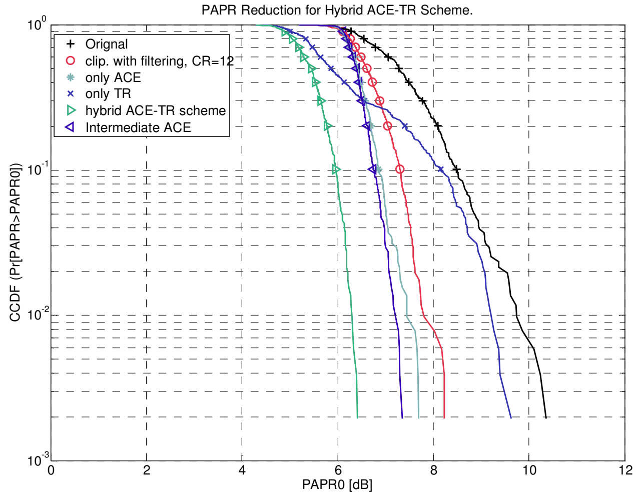

Figure 13. PAPR reduction using hybrid ACE-TR method. Type III

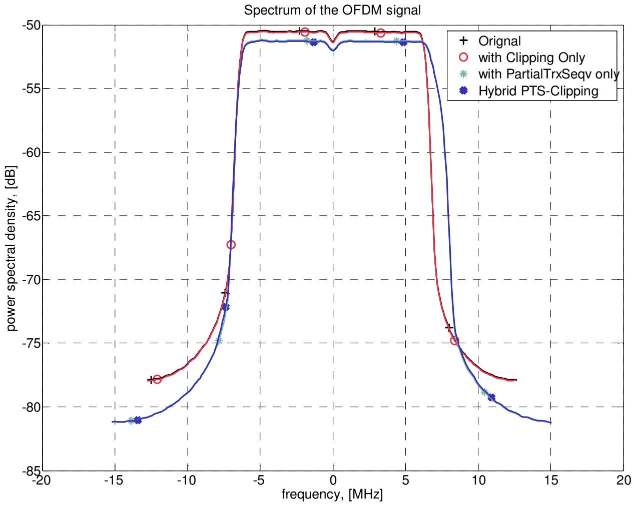

Figure 16. Spectr. of OFDM signal before/after PAPR reduction. Type III

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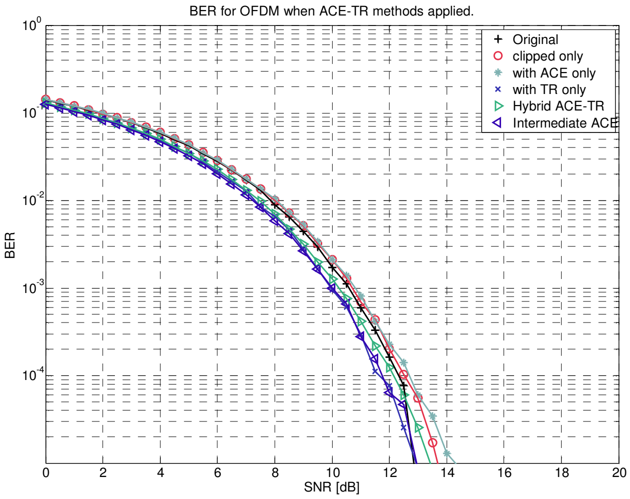

Figure 17. BER of OFDM signal before and after PAPR reduction.

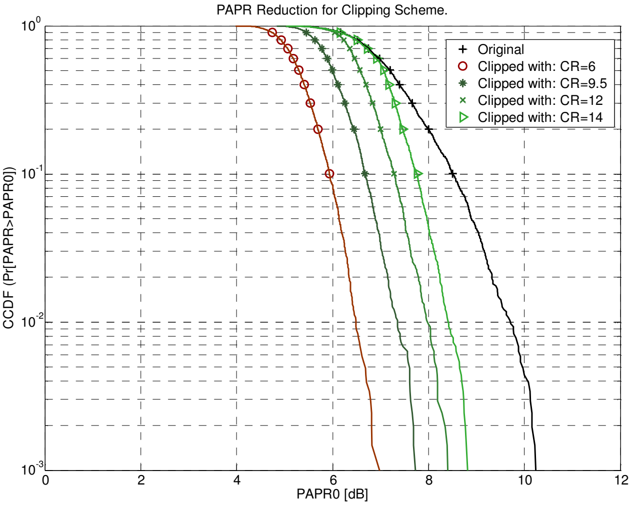

Figure 18. PAPR reduction using clipping method.

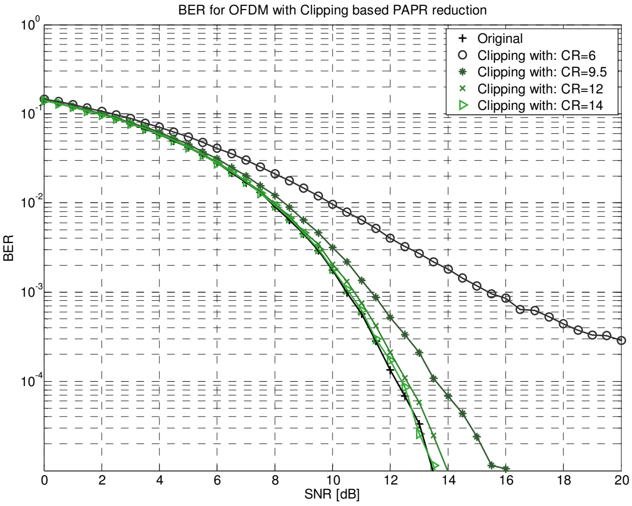

Figure 19. BER of OFDM signal befor/after clipping.

The results presented in this paper are obtained for OFDM frames with the repartition of non-data subcarriers as previously indicated in Figures 7, 8, and 9, with constellations of the pilot search space points identically with the constellations of the constellation used for data carriers.

The numerical results show that the proposed scheme improves the PAPR reduction in comparison with the use of only one of the component methods. This improvement is highlighted in this section with three cases.

In the first case, Figures 11 and 14 indicate the PAPR reduction and signal's frequency spectrum when the OFDM frame has the non-data subcarriers configuration as presented in Figure 7.

In Figure 11, it can be observed that the ACE method performs a better PAPR reduction while the applied TR method obtains a lower PAPR reduction than the clipping at a ratio of *CR*=12. A slight difference can be observed between the ACE applied on the initial OFDM frame and the extended OFDM frame containing the reserved non-data subcarriers. The hybrid ACE-TR provides better PAPR reduction since it accumulates the effects from the two methods.

Due to the insertion of the additional non-data subcarriers on the both sides of the original spectrum, the obtained signal presents an increased bandwidth as indicated in Figure 14.

In the second case, Figures 12 and 15 indicate the PAPR reduction and signal's frequency spectrum for the configuration shown in Figure 8.

Due to a different displacement of the non-data subcarriers; the TR method has a different efficiency for the PAPR reduction. Even if this method has smaller PAPR reduction, with the hybrid method still higher PAPR reduction is obtained. Also, this case presents a smaller increase of the bandwidth for the resulted OFDM signal than the one from the previous one.

In the third case, similarly, Figures 13 and 16 indicate the same signal parameters when the non-data subcarriers are located as is shown in Figure 9.

For the PAPR reduction, this case is quite similar with the first one. The difference consists on the spectrum of the resulted signal, which has a slightly asymmetrical shape.

Figure 17 shows that the BER performance is slightly influenced by the proposed PAPR reduction technique, being better than in case of simple clipping.

For a better evaluation of the performance of the proposed method, the PAPR reduction and corresponding BER characteristic of the clipping method are presented in Figure 18 and Figure 19, respectively.

The simulations shown that, if smaller values for the clipping ratio are considered, the clipping method obtains comparable PAPR reduction as the hybrid method do.

The drawback of this case is that the smaller *CR* values imply an increased signal distortion, and so a worst BER performance.

Therefore the presented numerical results shown that, in all cases, the hybrid ACE-TR method provides better PAPR reduction than in case of use of only one component method. Additionally, compared with clipping, the combined technique presents no degradation of the BER performance.

The computational complexity of the algorithm of the hybrid technique is given by the sum of the computational complexity of the component methods.

The ACE block performs one IFFT, one clip, one FFT and one vector shift per iteration. For the present simulations, we have limited the number of iterations in the ACE block to one, therefore the amount of operations for this block is $O(2+2\cdot N\cdot \log_2(N))$.

The TR block performs one change for a pilot subcarrier and one IFFT per iteration. Considering the applied algorithm and the size of the search space, a complete operation requires $O(M\cdot T\cdot (1+N\cdot \log_2(N)))$.

In practice, the amount of operations can be reduced if the time-domain signal corresponding to each single non-data subcarrier is pre-computed and stored in a nonvolatile memory. In this case the amount of operations is reduced to

$O(M\cdot T+N\cdot \log_2(N))$.

Based on these expressions, it can be observed that the amount of operations required by the hybrid method is bigger than the number of operations required by other PAPR reduction techniques and depends by number of data subcarriers and the size of the search space used by the TR block.

## VI. CONCLUSION AND FUTURE WORK

In this paper, we proposed a new PAPR reduction technique based on the combination of an active constellation extension method with a tone reservation method.

The paper presents the ACE and TR algorithms used within the hybrid technique. The interfacing of the two PAPR reduction blocks is also explained.

The simulation results show that the hybrid scheme realizes higher PAPR reduction for various OFDM frame formats. Similar results for PAPR reduction have been obtained for the case when TR block precedes the ACE block.

The two methods considered have various derivates, bringing different efficiency and performance. The ACE method may be implemented using different constellation restrictions, obtaining different PAPR reduction levels and BER performances. The TR method may use different set of values for the non-data subcarriers. Depending on this set, its computation complexity and PAPR reduction strength may significantly vary.

In future work, we will consider different ACE constraints and TR schemes with different numbers and various sets of values for the non-data carriers.

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