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New scheme for PAPR reduction in FBMC-OQAM systems based on combining TR and deep clipping techniques

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Article Info

ABSTRACT

Filter bank multi-carrier with offset quadrature amplitude modulation (FBMC-OQAM) system is a very efficient multicarrier modulation technique for 5G, but it suffers as all multicarrier designs from large peak-to-average power ratio (PAPR). Tone reservation (TR) is a method designed to solve this problem by reserving several subcarriers called tones in the frequency domain to generate a cancellation signal in the time domain to eliminate high peaks. In this paper, we suggest a serial combination of tone reservation (TR) method with an enhanced version of clipping called deep clipping (DC) method (TR&DC) to enhance the peaks (PAPR) mitigation in FBMC-OQAM signal model without significantly impacting the quality of transmission. Numerical results and analysis show that the new TR&DC approach allows better overall performance and offers remarkable gain in term of PAPR mitigation than the TR method, with similar BER performance to TR over additive white Gaussian noise channel and Rapp HPA model.

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1.   INTRODUCTION

The 5G air interface, expected for 2020, have to meet new requirements. Similarly, to 4G it should support users with great data rates and an important number of machine subscribers with low latency and energy efficiency [1]. Orthogonal frequency division multiplexing (OFDM) as a multicarrier technique used in 4G thanks to its closely spaced orthogonal tones, easy implementation and low complexity. Unfortunately, OFDM has some drawbacks that do not allow it to be adopted for 5G systems. Filter bank multicarrier with offset quadrature amplitude modulation (FBMC-OQAM) is the most interesting design proposed for the next 5G mobile communication physical layer [2], because it is very good localized in frequency domain, due to the specific prototype filter PHYDYAS which is well localized in both frequency and time. Thus, we can say that FBMC-OQAM assumes an optimal use of the frequential spectrum [3]. Nevertheless, the FBMC-OQAM suffers from large envelope fluctuations known as peak-to-average power ratio (PAPR) [4]. Furthermore, if a time domain signal with an important dynamic passes through a high power amplifier with insufficient linear zone, it could produce several in/out of band distortions [5], which lead to adjacent channel interference (ACI) (spectral regrowth) and to BER degradation.

To solve this high envelope fluctuations problem, various methods for PAPR mitigation have been suggested for OFDM system. The most used techniques are: clipping [6], coding schemes [7], nonlinear companding transforms [8], selected mapping (SLM) [9], tone reservation (TR) [10], and partial transmit

sequences (PTS) [11]. These methods reduce the PAPR of OFDM signal with generally negligible degradation of BER. Some techniques present high computational complexity as PTS and SLM.

Due to overlapping nature of FBMC-OQAM, a lot of new approaches to reduce PAPR have been recommended to get a better reduction than the conventional schemes. In [12], overlapped SLM (OSLM) technique was proposed to enhance the conventional SLM. Recently, in [13], the authors suggested dispersive SLM (DSLM) for the PAPR reduction in FBMC-OQAM system and dispersive TR. In [14], the authors suggested a multi-block joint optimization (MBJO) to fit the PTS method with the overlapping nature of the FBMC-OQAM scheme. In [15], the TR scheme for reducing the PAPR in FBMC-OQAM signal was enhanced by using the sliding window (SW) algorithm. Also, in [16-18], the authors have proposed an extension of the classical TR and ACE methods to the FBMC-OQAM and a novel method called Multi-blocks selective mapping (MB-SLM). In [19], a joint solution with SLM and TR was addressed to achieve better PAPR reduction. A solution was proposed in [20], named TR-PTS hybrid approach with a multi data block-PTS by taking advantage of the FBMC-OQAM symbol overlaps. The crucial drawback of all these proposed methods is their high numerical complexity.

In this paper, we propose a new hybrid solution called TR&DC for PAPR mitigation in FBMC-OQAM signals which combines tone reservation (TR) and deep clipping (DC) techniques. For the new TR&DC scheme, the first step is to treat the original FBMC-OQAM signals via the TR approach. Since some peak power of the original signals mostly occurs at some positions, we only need to perform a deep clipping function for achieving the best reduction. The simulation results are used to show the effectiveness of the proposed TR&DC scheme in reducing the power envelope fluctuations for FBMC-OQAM signals.

The organization of this paper is as follows: In section 2, we introduce the FBMC-OQAM signal and PAPR in detail, also tone reservation and deep clipping techniques for PAPR reduction, and we present the proposed TR&DC scheme. In section 3, we show our simulation results of the new TR&DC scheme and discussions. Finally, a general conclusion is stated in section 4.

2. RESEARCH METHODS
2.1. FBMC-OQAM signal model and PAPR

The FBMC-OQAM transmitter model [21] is presented in Figure 1, where N represents the subcarriers amount and M is the number of input symbols. The input symbol X_m^n is written as follows:

$$X_m^n = R_m^n + jI_m^n, \quad 0 \le n \le N-1, \quad 0 \le m \le M-1 \tag{1}$$

I_m^n and R_m^n, are imaginary and real parts of the m th complex symbol X_m^n on the n th subcarrier respectively. For Offset QAM, the both real and imaginary parts of the QAM symbols are spaced in time domain by $T/2$, where T is the symbol duration. After that, the complex symbols are passed on a filter bank of transmission. The m th FBMC-OQAM transmission symbol can be obtained by combining all subcarriers signals, which is written as follows:

$$S_m^{FBMC}(t) = \sum_{n=0}^{N-1}[R_m^n\xi(t-mT) + jI_m^n\xi(t-mT-\tfrac{T}{2})]e^{jn(\frac{2\pi}{T}t+\frac{\pi}{2})} \tag{2}$$

where $\xi(t)$ is the prototype filter impulse response.

We consider the PHYDYAS filter (physical layer for dynamic spectrum access and cognitive radio filter) as the prototype filter. PHYDYAS filter [22] design is based on the frequency sampling method where the impulse response is:

$$\xi(t) = \begin{cases} \frac{1}{\sqrt{B}}\left[1 + 2\sum_{k=1}^{\Gamma-1}(-1)^k G_k \cos\left(\frac{2\pi kt}{\Gamma T}\right)\right], & t\epsilon[0,\Gamma T] \\ 0 & elsewher \end{cases} \tag{3}$$

where:

$$B = \Gamma T[1 + 2\sum_{k=1}^{\Gamma-1} G_k^2] \tag{4}$$

$$G_0 = 1; G_1 = 0.9716960; G_2 = \frac{1}{\sqrt{2}}; G_3 = \sqrt{1-G_1^2}$$
$$G_k = 0 \text{ for } k > 3 \quad \text{and} \quad G_k = G_{-k} \text{for } k < 0 \tag{5}$$
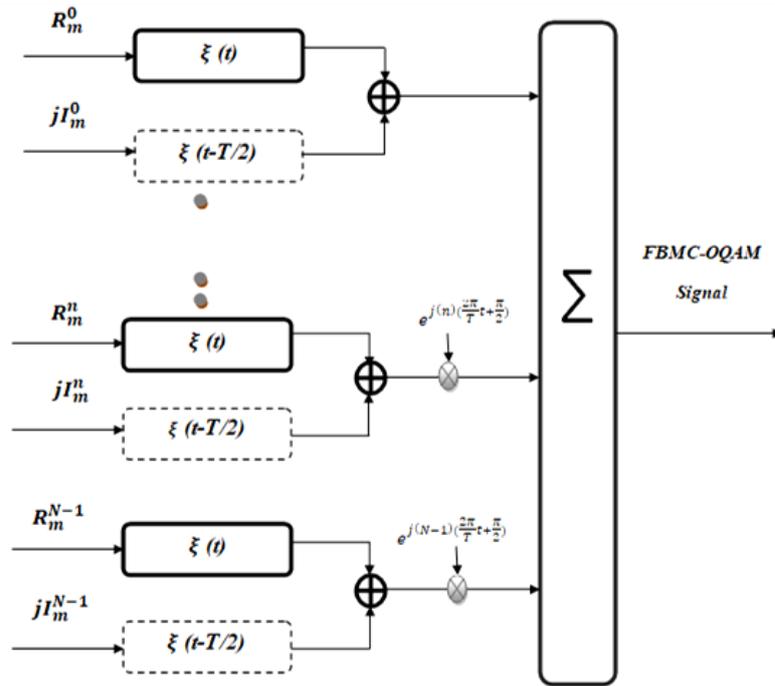
Figure 1. The FBMC-OQAM transmitter

From the overlapping process of FBMC-OQAM data symbols depicted in Figure 2, it is clear that every data of block signal consists of two parts real (R) and imaginary (I)which are spaced by $T/2$. Additionally, the length of one data block is$(\Gamma + 1/2)T$. The length of M total consecutive data blocks is $(\Gamma + M - 1/2)T$. The symbol $S_1(t)$ overlaps with the following $\Gamma - 1$ data block signal. The Mtotal FBMC-OQAM symbols are given as:

$$S(t) = \sum_{m=0}^{M-1} S_m^{FBMC}(t), 0 \leq t \leq \left(M + \Gamma - \frac{1}{2}\right)T \tag{6}$$
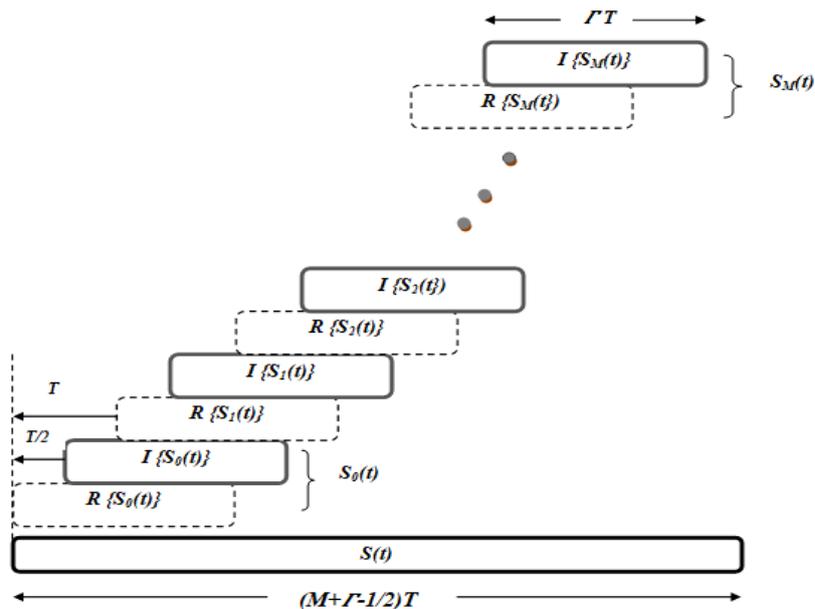
Figure 2. The FBMC-OQAM signal structure

According to the previous paragraph, we need to redefine PAPR for this system. We consider the FBMC-OQAM burst transmission; there are both initial transition phase and final one in an FBMC-OQAM burst. Therefore, the signal in few area of the transition is very small. The power peak of the FBMC-OQAM signal appears in the middle zone, where we can calculate the PAPR of FBMC-OQAM signals. In this respect, we consider that the both transition phases (initial and final) are equal to $(\Gamma + 1/2)/2$ symbol periods. The middle part is from $(\Gamma + 1/2)N/2$ to $MN + (\Gamma + 1/2)N/2$ with MN points that are then divided into M intervals equally with period T. Thus, the PAPR of each interval is defined by (7). We use CCDF (complementary cumulative distribution function) to analyse the PAPR performance of FBMC-OQAM signals, which is determined as the probability that PAPR surpass a specific threshold $PAPR_{TH}$.

$$PAPR \ (dB) = 10 log_{10} \frac{max_{it \le t \le (i+1)T}(|S(t)|^2)}{E(|S(t)|^2)} \tag{7}$$

where $E\{\cdot\}$ denotes the expected value and $0 \le i \le M$.

$$CCDF \ (PAPR) = Pr(PAPR > PAPR_{TH}) = 1 - \left(1 - e^{-\gamma}\right)^N \tag{8}$$

2.2. Tone reservation technique for FBMC-OQAM PAPR reduction

Tone reservation (TR) was first introduced in [23]. The basic idea of TR scheme is to isolate energy used to cancel high peaks to a predefined set of subcarriers, termed peak reserved tones (PRTs). These reserved subcarriers do not transport any useful information and are orthogonal to the data tones (DTs). In other words, the TR scheme consists to add a time domain signal $c(t)$ to the original signal $s(t)$ to reduce its peaks as shown in Figure 3. But the resulting PAPR of $(s(t) + c(t))$ must be lower than the original PAPR of $s(t)$. In the TR based on an iterative clipping filtering algorithm, the total N tones are divided into P peak reduction tones (PRTs) and $N - P$ data tones. The positions of the PRTs are known by both transmitter and receiver. The detailed procedure of TR scheme for FBMC-OQAM signals is described as follows:

First, we divide the mth data block X_m^n in frequency domain into a data vector Z_m^n and peaks (PAPR) reduction vector C_m^n given as:

$$X_m^n = Z_m^n + C_m^n = \begin{cases} C_m^n, & for & n \in P \\ Z_m^n, & for & n \in P^C \end{cases} \tag{9}$$

$$\begin{cases} C_m^n = 0, & for & n \in P^C \\ Z_m^n = 0, & for & n \in P \end{cases} \tag{10}$$

where $P = \{n_1, n_2, \dots, n_P\}$ is the set of tones reserved for peaks canceling, P^C is the set of data tones, and P^C is the complement set of P in $\mathbb{N} = \{0, 1, \dots, N-1\}$.
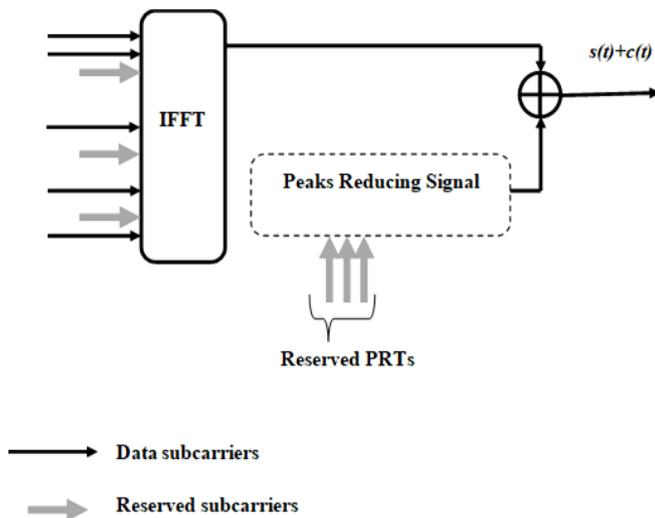
Figure 3. Tone reservation principle

The data subcarriers in time domain $z(t)$ are produced by N point IFFT operation of Z_m^n. Then, $z(t)$ is clipped to a threshold ω as:

$$\overline{z(t)} = \begin{cases} z(t) & if\ |z(t)| \leq \omega \\ \omega e^{j\varphi_z} & if\ |z(t)| > \omega \end{cases} \tag{11}$$

where $z(t) = |z(t)|e^{j\varphi_z}$, φ_z is the phase of $z(t)$. We calculate the original clipping noise $y(t)$ as:

$$y(t) = \overline{z(t)} - z(t) \tag{12}$$

$$C_m^n = \begin{cases} Y & n \in P \\ 0, & n \in P^C \end{cases} \tag{13}$$

where $Y = FFT(y)$. Finally, we add the time domain peaks reduction signal $c(t)$ to $s(t)$ and the PAPR of the new TR FBMC-OQAM signal can be expressed as:

$$PAPR_{TR\_scheme}(dB) = 10log_{10} \frac{max_{iT \leq t \leq (i+1)T}|s(t)+c(t)|^2}{E[|s(t)|^2]} \tag{14}$$

2.3. Deep clipping technique

Deep clipping [24] is an enhanced version of clipping. It has been suggested to solve the problem of peaks regrowth. The classical clipping is modified to deeply clip the high amplitudes. A parameter has been delivered referred to clipping depth factor in order to manage the depth of the clipping. The deep clipping (DC) function shown in Figure 4 can be expressed as below (where $0 \leq \rho \leq 1$ is the clipping depth factor and A is clipping level).

$$\widetilde{s(t)} = \begin{cases} s(t) & |s(t)| \leq A \\ A - \rho(s(t) - A) & A < |s(t)| \leq \frac{1+\rho}{\rho}A \\ 0 & |s(t)| > \frac{1+\rho}{\rho}A \end{cases} \tag{15}$$
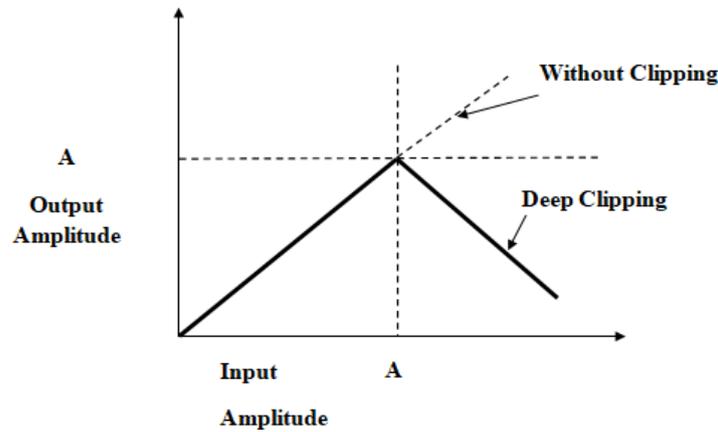
Figure 4. Deep clipping function

2.4. Proposed combined TR&DC technique for FBMC-OQAM PAPR reduction

In this subsection, we describe our proposed hybrid TR&DC scheme which combines tone reservation (TR) and deep clipping (DC) methods for PAPR reduction in FBMC-OQAM signals as shown in Figure 5. These two schemes can be complementary, the TR method reduces some peaks in a FBMC-OQAM symbol, but a few peaks of the complex symbol cannot be canceled by this way, and will be affected by the non-linearity of the HPA. For this, we propose to apply the deep clipping function to deeply cancel any high peaks. This suggested PAPR reduction technique combines the advantages of linearity from the first step (TR) with the reduced computation complexity of the second step (DC), providing a better PAPR reduction with good efficiency.
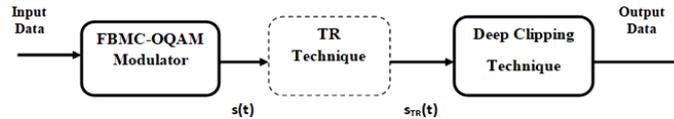
Figure 5. The new combined TR&DC scheme

The steps of the new proposed TR&DC algorithm can be summarized as:

Proposed algorithm

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1. Specify a desired clipping threshold ω, the numbers of iteration I and reserved tones P
   for TR.
2. Generate the time domain signal s(t) of the M data blocks at the output of the FBMC-OQAM
   transmitter side using (6).
3. Clip the FBMC-OQAM signal at ω by using (11).
4. Generate a peak power cancelling signal by :
   - Calculate the clipping noise using equation (12) y(t).
   - Convert it to the frequency domain Y(f).
   - Remodulate C(f) to get c(t).
5. Calculate the new TR FBMC-OQAM by adding c(t) to (t) .
6. Clip the new TR FBMC-OQAM signal by deep clipping function (15) at threshold A and the
   clipping depth factor ρ.
7. Calculate the PAPR of the new combined TR&DC FBMC-OQAM signal by (7).
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3. SIMULATION RESULTS AND DISCUSSIONS

In this section, the simulation results of the new combination TR&DC for the PAPR mitigation in FBMC-OQAM signals are represented. The considered FBMC-OQAM system is taken with $N = 64$ subcarriers. The prototype filter is PHYDYAS with overlapping factor equal to $\Gamma = 4$, the length of the filter is ΓN. For the TR scheme, PRTs are $P = 8$. All data are $4QAM$ modulated. The iteration times for the TR is $I = 8$ and the clipping level is taken $\omega = 1.8$. For deep clipping technique the depth factor is taken $\rho = 0.6$ and $A = 3$. PAPR performances are analyzed using CCDF plots.

From Figure 6 (a), we see that the PAPR of unchanged FBMC-OQAM, for a $CCDF = 10^{-3}$ the PAPR threshold is $10.2\ dB$. When we apply TR technique, it significantly reduces from $10.2 dB$ to $7.8\ dB$ for the same $CCDF = 10^{-3}$. In the hybrid TR&DC FBMC-OQAM, for a $CCDF = 10^{-3}$ the PAPR is $7\ dB$. The reduction gain of the new combination TR&DC is about $3.2\ dB$. We can remark that, this new TR&DC method presents an important gain in term of reduction. PAPR reduction gain depends on many parameters such as clipping level, the number of peak reduction tones, clipping depth factor and the number of iterations.

The temporal evolution of the new TR&DC scheme, TR and the original FBMC-OQAM signal are presented in Figure 6 (b). Peaks power of the considered signals appears at some points. Compared with the original signal, the combination TR&DC can efficiently cancel the peaks power of the signal better than the TR only. In Figures 7 (a) and (b), we show the PAPR reduction of the suggested TR&DC scheme with different clipping thresholds ω and different depth factors ρ with fixed parameters: $P = 8$, $I = 8$, $A = 3$, $p = 0.6$. ω is selected as $\omega = 2.42, 2, 1.8, 1.6$ respectively, and ρ is selected as $\rho = 0, 0.2, 0.4, 0.6$. It is illustrated that the variation of the threshold (ω) and the depth factor (ρ) may not contribute in reducing PAPR. Because in both figures, all results are around $7dB$ with a slight difference. Different numbers of PRTs (P) of the new scheme are depicted in Figure 7 (c). When the number of PRTs is $P = 2, 4, 8, 12$, with fixed parameters: $\omega = 2$, $I = 8$, $A = 3$, $p = 0.6$. It can be observed that for $P = 12$ compared with the original signal at $CCDF = 10^{-3}$, the PAPR reduction gain of the new TR&DC is $3.1\ dB$. Evidently, increasing the number of PRTs could considerably enhance the PAPR mitigation for the TR&DC approach. Then, we have executed the same algorithm using different iterations $I = 2, 8, 16, 40$ when the fixed parameters are $= 2$, $P = 8, A = 3, p = 0.6$ as shown in Figure 7 (d). From Figure, we note that the PAPR threshold decreases as the increasing of I. When $I = 40$ and $CCDF = 10^{-3}$, the threshold value of the new TR&DC with $\omega = 2$ is $6.2\ dB$. As simulation results show, the TR&DC method have enhanced the peaks mitigation (PAPR) and we just have to select the optimal combination of parameters to get the best performance.

The BER simulations are shown in Figure 8 for the new TR&DC, TR and the original FBMC-OQAM when the channel between the transmitter and the receiver is taken as an additive white Gaussian noise (AWGN) channel and at various values of SNR. From Figure, we see that the TR plot coincides with TR&DC plot and present acceptable BER performance.

(a)

(b)
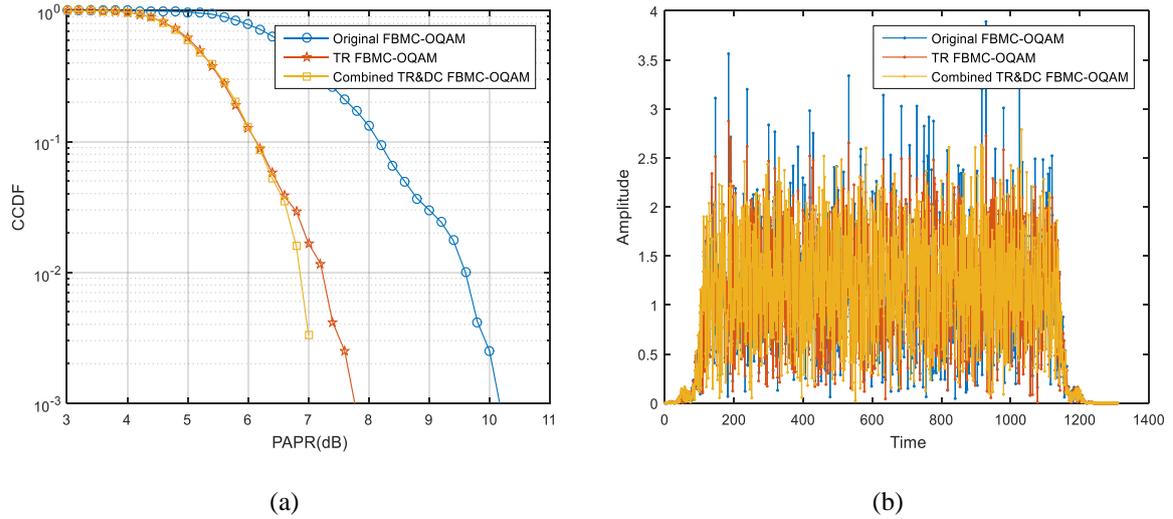
Figure 6. CCDFs and time evolution of TR&DC, TR schemes and original FBMC-OQAM signal

(a)

(b)

(c)

(d)
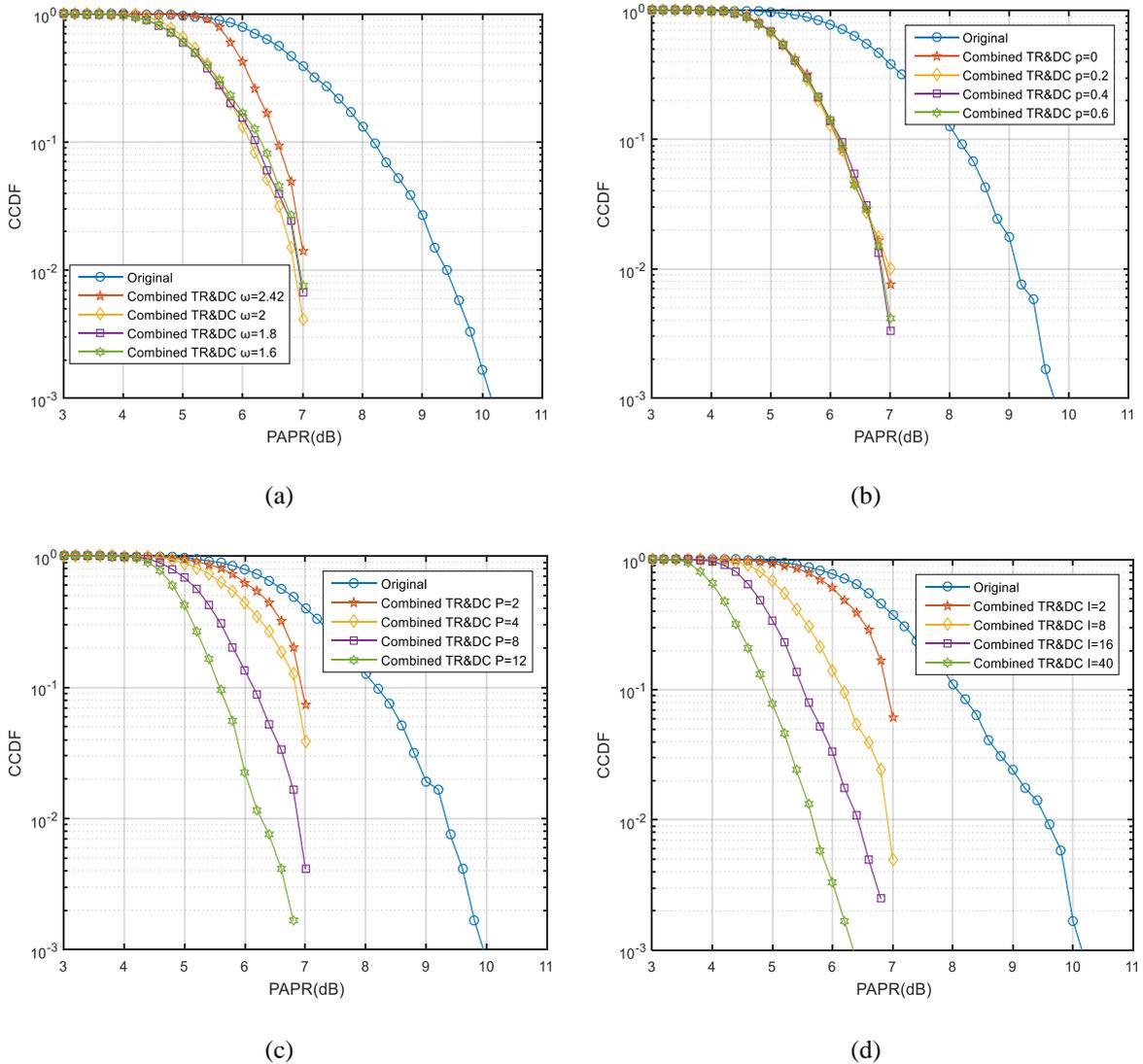
Figure 7. CCDFs plots of the new TR&DC scheme using different parameters
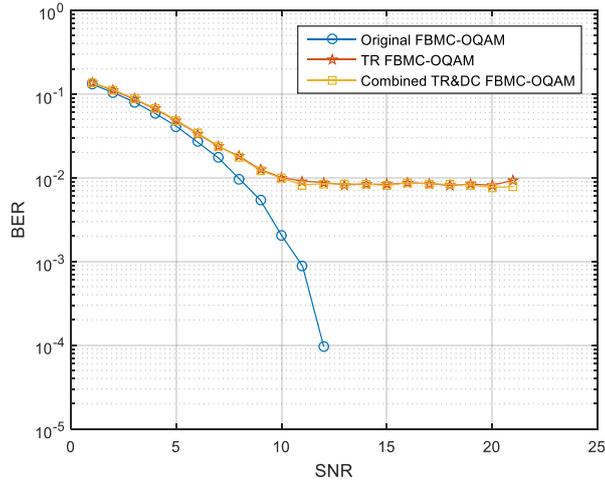
Figure 8. BER of TR&DC, TR schemes and original FBMC-OQAM over AWGN channel

Finally, a nonlinear high power amplifier model is introduced to observe the performance of our TR&DC method in term of BER performance. The HPA follows the Rapp model with a smoothness factor $\beta = 2$ that controls the transition between the linear area of the HPA and the saturation one. The Rapp model [25] presents only AM/AM conversion. This one can be denoted as:

$$F_{AM/AM}(s(t)) = \frac{s(t)}{\left(1 + \left(\frac{s(t)}{A_{sat}}\right)^{2\beta}\right)^{\frac{1}{2\beta}}} \tag{16}$$

$$F_{AM/PM}(s(t)) = 0 \tag{17}$$

where the smoothness factor is all time $\beta > 0$. From Figures 9 (a) and (b), we can observe that the proposed TR&DC and TR technique perform similarly even in the presence of Rapp HPA in both scenarios $IBO = 0\ dB$ and $IBO = 7\ dB$ respectively. But as we know, the BER results depend on the IBO (the BER measurements improve when the IBO increases for the original FBMC-OQAM signal).

(a)

(b)
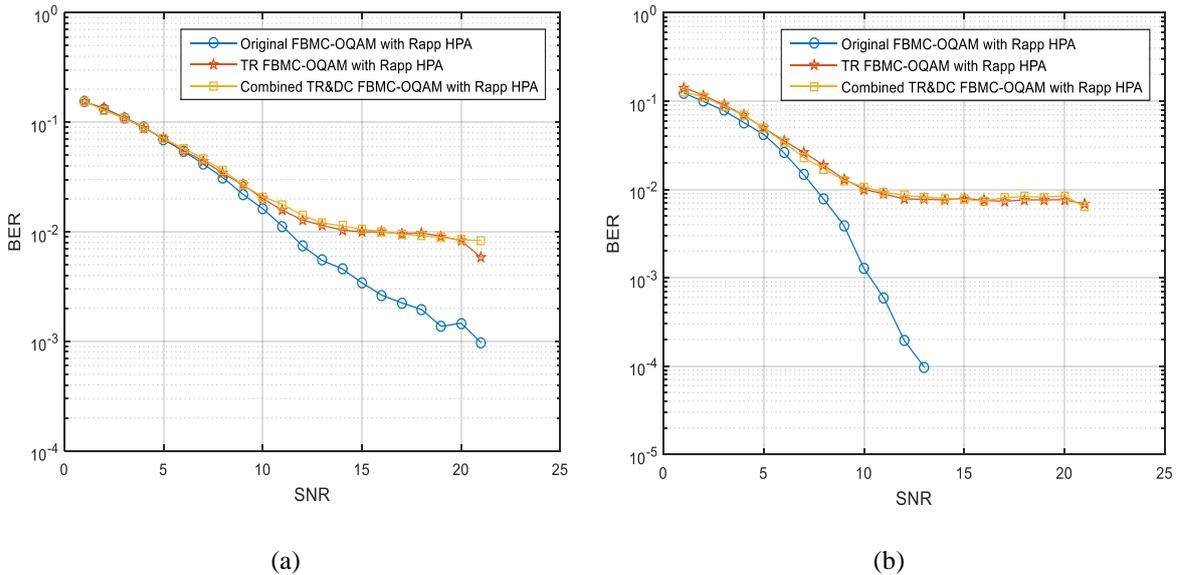
Figure 9. BER of TR&DC, TR schemes and original FBMC-OQAM with Rapp HPA over AWGN channel,
(a) IBO=0dB, (b) IBO=7dB

4.   CONCLUSION

Theoretically the TR cannot eliminate all high power peaks present in multicarrier signals such as in FBMC-OQAM. The study presented in this article was used to evaluate the possibility to associate a deep clipping technique which is better than the classical clipping technique with TR method for the FBMC-OQAM waveform, resulting in a good compromise between the backward compatibility, the linearity of the TR method and low complexity, simplicity of the deep clipping. In this paper, large number of simulations have validated that our suggested TR&DC method can achieve excellent PAPR mitigation. From the simulation results, the new proposed TR&DC method for reducing PAPR in FBMC-OQAM signals present an improvement in PAPR performance compared to the TR scheme and original FBMC-OQAM signal. For the new proposed TR&DC scheme, we can adjust parameters of each technique to get the optimal performance. In addition, over both AWGN channel and HPA with Rapp model the new TR&DC and TR techniques perform similarly in term of BER performance.

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