Energy efficiency comparison of IICM and Clipping using real power amplifier

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***Abstract*—Peak-to-Average Power Ratio (PAPR) is an important parameter in digital communications. Furthermore, 5G Communication Systems will be based on the new multicarrier modulation schemes. Hence, it is desirable to investigate the problems of PAPR in 5th generation communication systems. In this paper, first a detailed introduction of multicarrier modulation and PAPR problem are given. Than we compared two PAPR reduction methods : Iterative Invertible Clipping Method (IICM) and clipping with filtering method in terms of Error Vector Magnitude (EVM) for the same PAPR value. The simulation results shows that there is a gain of 1dB between the two methods.**

***Index Terms*—IICM, PAPR, 5G, PA, EVM.**

I. Introduction

Nowadays, wireless communication systems are more and more present in our daily life and they tend to replace the excessive use of cables. Although high-speed ADSL-type connections are increasing in number around the world, they do not provide the flexibility of use that a wireless radio network provides. To improve the quality of service they offer, researchers are preparing the arrival of the future generation called 5th Generation (5G) [1].

Orthogonal Frequency Division Multiplexing (OFDM) present in several telecommunication standards are today the modulation technique making it possible to best meet these requirements. digital modulators and demodulators associated with OFDM and MC-CDMA modulation have an acceptable digital complexity (logarithmic) for applications with low computing resources. The signals with multi-carrier modulations have a non-constant envelope, which creates a major difficulty when amplifying the power of multi-carrier systems.

To overcome this constraint, a parameter called the Crest Factor (CF) [2] is defined which makes it possible to identify and quantify this characteristic of multi-carrier signals. The crest factor is closely related to another entity commonly known in the literature, under the name of PAPR [2] and which establishes the relationship between the maximum power (maximum amplitude) and the average power of the signal.

The power amplifier (HPA) [3] is the means of giving the necessary power allowing the transmission of the signal towards the receiver without it being attenuated. It is therefore a key element in a communication chain insofar as it has a preponderant influence on the overall balance of the transmission chain in terms of energy consumption and in terms of the quality of the transmitted signal, the Bit Error Rate (BER) is evaluated according to the Signal to Noise Ratio (SNR). In fact, the power amplifier alone represents approximately two thirds of the energy consumption of a transmission chain on the transmitter side. It is therefore important to operate the amplifier with the greatest possible energy efficiency, especially for systems with low energy resources such as mobile terminals generally having low energy autonomy.

Among the techniques for reducing PAPR in OFDM system, we have retained the invertible clipping method with filtering, as already proposed by Ragusa [4]; this proposal aims to improve the classical technique [5] of PAPR reduction by introducing a clipping function with a smoother saturation. At the reception level, the application of the inverse of the clipping function is considered as a possible plausible solution to improve the performance of the BER. In fact, the inverse function compensates for some of the distortions (IESNL for Non-Linear Interference Between Symbols) introduced by clipping.

The proposed method adopted in this paper is called the Iterative Invertible Clipping Method (IICM) [6]. It uses a third degree polynomial to deliver the invertible clipping function, where the inverse function is obtained exactly by adopting the radical solution of the 3rd degree equation, hence better BER performance. In addition, the IICM method can reach higher degrees than Ragusa, using the iterative process. We will compare the IICM method clipping method with filtering in terms of EVM, for the same PAPR valus.

The remaining of this paper is organized as follows: In Section II, a brief presentation of both conventional clipping and IICM methods will be given. In Section III, we present the system model used for the comparison of the two techniques. Simulation results comparing the two approaches are shown in Section IV. Finally, the conclusion of this work is given in Section V.

II. System model

A. Waveform description

OFDM is an orthogonal multicarrier system based on a rectangular shaping filter and the Inverse Fast Fourier Transform

(IFFT). The n^{th} sample of the l^{th} OFDM symbol can be written as:

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} d_{k,l} e^{\frac{j2\pi kn}{N}}, \; n = 0, 1, \ldots, N-1, \quad (1)$$

where $\boldsymbol{d}_m = \left[d_{0,l}, d_{1,l}, \ldots, d_{N-1,l}\right]$ is the emitted vector of complex M-QAM symbols, l is the index of the OFDM symbol, k is the index of the subcarrier, and N is the total number of subcarriers.

B. PA model

In this paper, a realistic PA model is used. The PA is a 2.6 GHz class-AB amplifier based on GaN transistor with a power gain of $19dB$, maximum output power of $56W$ and a power added efficiency (PAE) of 70% [7]. The AM/AM and PAE characteristics are shown in Fig.1

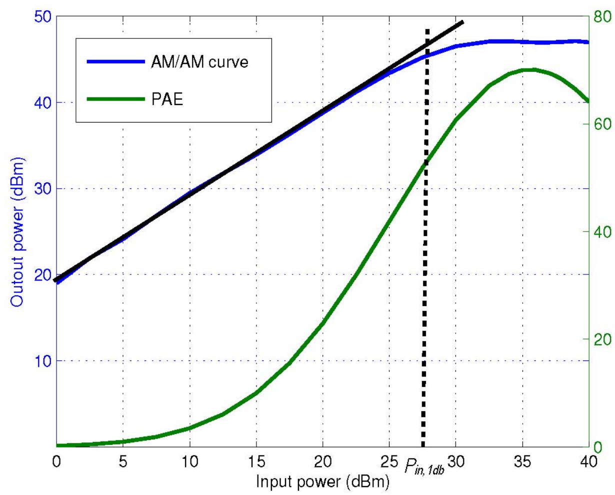

Fig. 1: Output power, PAE vs. input power of GaN PA [10].

III. Iterative Invertible Clipping Method and clipping techniques presentation

A. Clipping technique

Intuitively, this method is very simple to understand, because it consists of clipping the signal amplitude to a predetermined threshold to reduce the maximum amplitude of the signal at this threshold. This process therefore has the effect of reducing the power variation of the signal and consequently of reducing the sensitivity of the signal to non-linearities. The resulting signal, if it remains compatible, is degraded and will not have the nominal performance at reception. Moreover, since saturation is itself, in principle, a non-linear element, all the defects intrinsic to this type of element will be found here [9]. Numerous clipping methods have been developed, as shown by the works in [10], [11]. This technique was proposed at the beginning of the implementation of terrestrial OFDM (DVB-T), in the years 1997 [11]. Thus, a signal x will be clipped according to the following law:

$$f(x) = \begin{cases} x & |x| \leq A \\ Ae^{j\varphi(x)} & |x| > A \end{cases} \quad (2)$$

where $y = f(x)$ is the resulting signal, A is the limiting amplitude or clipping threshold and $\varphi(x)$ is the phase of the signal x. This technique, like all distortion techniques, generates the three classic problems of a nonlinearity:

1) Side lobe rise from intermodulation products.
2) Generation of interference between non-linear symbols (provided that convolutional filtering is present).
3) Generation of noise in the useful band: noise with a particular structure because it corresponds to the different intermodulation products that fall into the useful band.

Point (1) can easily be treated by a frequency selective filter located just after the clipping. This filter has been proposed in [101], so we can say that it is part of the technique. This filter is necessary to decrease the ACPR, which measures the rise of the side lobes. For current OFDM standards, this filter does not really add complexity because it is defined in the standard to limit the channel band.

D.Guel in his PhD thesis [9] proposed a frequency filtering method based on digital filtering (FFT/IFFT) to deal with point (3). The articles of L.J Cumin [11] can be considered as the reference on this method. They analyze the effects of the 3 previous points on the power spectral density and on the BER. Of course, the latter is degraded by several dB because of the clipping noise in the band. In [12], K.R. Panta and J. Armstrong show that this problem is less important when the signal passes through a frequency selective channel. They show, in fact, that the error rate is mostly due to subcarriers that are highly affected by the channel, and in this case the contribution of the clipping noise on the BER is very small. Another analysis of this problem shows that the degradation in signal-to-noise ratio can be effectively mitigated by using a high performance code such as the combination of turbo code (TC) and low density parity check (LDPC) code [13].

B. Description of reversible clipping

The invertible clipping technique was recently proposed by S. Ragusa [4]. The main idea of this technique is to mask an unknown non-linearity by a known and more important non-linearity which is invertible on reception as shown in figure 2. It takes its origin in the studies of nonlinear automatics. It should be noted that the clipping is downward compatible if the inversion function is not performed on reception. Otherwise it results in a degradation of performance that must be taken into account.

1) Transmitter: As mentioned earlier, the invertible clipping function is performed separately on the components $I_{(b)}(n)$ and $Q_{(b)}(n)$ of the complex MC-CDMA signal $z_{(b)}(n)$, at the transmitter, using the following equations:

$$I_{(b)}^{clp}(n) = -\frac{1}{2R_I^2}\left(\left[I_{(b)}(n)\right]^3 - 3R_I^2\left[I_{(b)}(n)\right]\right) \quad (3)$$

$$Q_{(b)}^{clp}(n) = -\frac{1}{2R_Q^2}\left(\left[Q_{(b)}(n)\right]^3 - 3R_Q^2\left[Q_{(b)}(n)\right]\right) \quad (4)$$

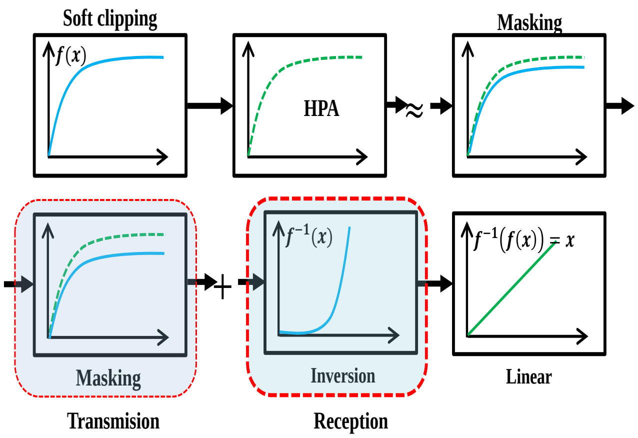

Fig. 2: Invertible clipping (masking of the power amplifier).

The clipped signal $z^{clp}_{(b)}(n)$ regenerated by two components (I/Q) for the bth symbol is given by the following relation:

$$z^{clp}_{(b)}(n) = I^{clp}_{(b)}(n) + jQ^{clp}_{(b)}(n) \quad (5)$$

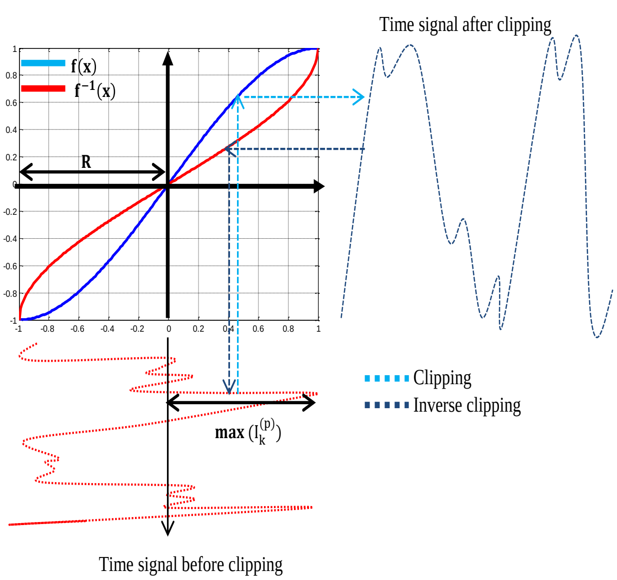

Fig. 3: Principle of the invertible iterative clipping method (example 3 iterations).

This method is repeated N_{iter} iterations; where: $z_{(b)}(n)$ and $z^{clp}_{(b)}(n)$ are replaced by $z^{j}_{(b)}(n)$ and $z^{j+1}_{(b)}(n)$, the initial signal is considered as $z^{0}_{(b)}(n) = z_{(b)}(n)$ to be able to execute the iterative process, for this purpose we named it the Iterative Invertible Clipping Method (IICM). Moreover, this method can reach higher degrees than S.Ragusa, as an example, we can reach an optimized sixth degree polynomial using only two iterations, while three iterations provide a ninth degree polynomial and so on. Figure 3 represents the principle of the Iterative Invertible Clipping Method (IICM).

2) FFT/IFFT-based digital filtering: Let $\tilde{z}^{clp}_{(b)}(n)$ be the signal at the output of the FFT/IFFT, as shown in Figure 4, the filtering consists of an FFT operation followed by an IFFT operation. The FFT transforms the time samples $z^{ecr}_{(b)}(n)$ into frequency components $Z^{ecr}_{(b)}(k)$ of which those positioned on the out-of-band (OOB) carriers are set to zero, i.e. :

$$\tilde{Z}^{clp}_{(b)}(k) = \begin{cases} Z^{clp}_{(b)}(k), & k \in \left[1; \frac{N}{2}\right] \cup \left[N\left(L - \frac{1}{2}\right); NL\right] \\ 0, & k \in \left[\frac{N}{2} + 1; N\left(L - \frac{1}{2}\right) - 1\right] \end{cases} \quad (6)$$

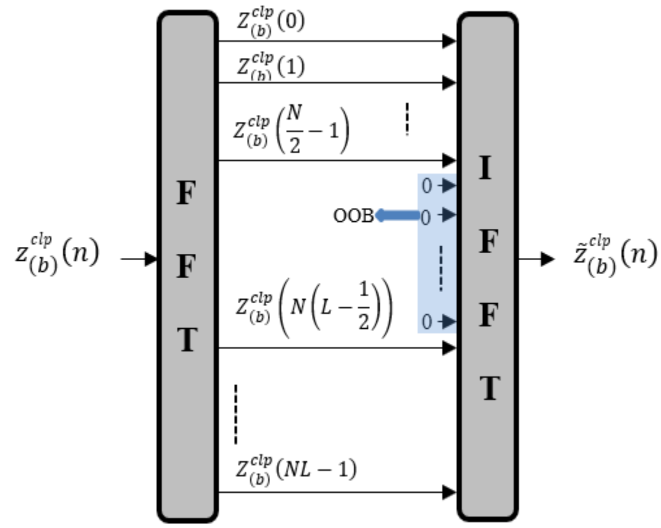

Fig. 4: Principle of the invertible iterative clipping method (example 3 iterations).

The frequency components $\tilde{Z}^{clp}_{(b)}(k)$ are then transformed to the time domain by the IFFT. The $\tilde{Z}^{clp}_{(b)}(k)$, however, must meet the specifications of the transmit mask. The resulting filter is time-dependent, and rejects discrete out-of-band frequency components. This means that it does not cause any distortion in the MC-CDMA signal band. Since the filter works symbol by symbol, it cannot cause any interference between symbols.

C. Iterative Invertible Clipping Method technique

This method was proposed in [6] known as IICM which uses a polynomial of degree 3 to derive the invertible clipping function, in improvement of that of Ragusa which uses a polynomial of degree 5. In addition, the Ragusa method uses an approximation in the inverse function, which can lead to degradation of the performance of the transmission system, unlike the proposed IICM method, the inverse function is used exactly.

The algorithm performing the IICM approach is summarized below.

It should be mentioned that the proposed algorithm is executed for MC-CDMA symbols.

In order to be able to easily follow the different steps of this algorithm, the digital filter FFT/IFFT has been designated by the function Ω.

Algorithm 1 Invertible iterative clipping (IICM).

1: Initialization : $b = 1$, $m = 1$
2: $R_I = max\,|I_b(n)|_{n=0,\dots,NL-1'}$
3: $R_Q = max\,|Q_b(n)|_{n=0,\dots,NL-1'}$
4: $I^{cl}_{(b)}(n) = -\frac{1}{2R_I^2}\left(\left[I_{(b)}(n)\right]^3 - 3R_I^2\left[I_{(b)}(n)\right]\right)$
5: $Q^{cl}_{(b)}(n) = -\frac{1}{2R_Q^2}\left(\left[Q_{(b)}(n)\right]^3 - 3R_Q^2\left[Q_{(b)}(n)\right]\right)$
6: $z^{cl}_{(b)}(n) = I^{cl}_{(b)}(n) + jQ^{cl}_{(b)}(n)$
7: $\tilde{z}^{cl}_{(b)}(n) = \Omega\left[z^{cl}_{(b)}(n)\right]$
8: $\tilde{z}^{cl}_{(b)}(n) = \tilde{I}^{cl}_{(b)}(n) + j\tilde{Q}^{cl}_{(b)}(n)$
9: $I_{(b)}(n) = \tilde{I}^{cl}_{(b)}(n)$ and $Q_{(b)}(n) = \tilde{Q}^{cl}_{(b)}(n)$
10: $m = m + 1$
11: **if** $m \leq N_{iter}$ **then**
12: go to 3
13: **else**
14: $z_{(b)}(n) = I_{(b)}(n) + jQ_{(b)}(n)$, $m = 1$
15: **end if**
16: $b = b + 1$
17: **if** $b \leq N_{sym}$ **then**
18: go to 1
19: **end if**
20: end

D. Improve EVM performance

Let the signal at the transmitter level be Y, with :

$$Y = [y_0, y_1, \dots, y_{N-1}]^T \tag{7}$$

where T is the matrix transposon.

It can be also written as follows :

$$Y = I + JQ \tag{8}$$

Using the inverse function of the function used in the clipping we get the following

$$Y_{inv} = I_{inv} + JQ_{inv} = f^{-1}_{R_I}(I) + j f^{-1}_{R_Q}(Q) \tag{9}$$

By entering the fft operation on the signal obtained, we find

$$x_{inv} = FFT\{Y_{inv}\} \tag{10}$$

Let the constellation points closest to the signal x_{inv} be $\hat{x}_{inv}$. We calculate the difference between them and write the result as a polynomial of degree P according to the following relationship

$$u = x_{inv} - \hat{x}_{inv} \tag{11}$$

For this, we follow the following steps :

- We calculate the IFFF of the signal u, we call it U, where :

$$U = IFFTu \tag{12}$$

- The real and imaginary part of the obtained signal are set, and we write the following

$$U = U_I + jU_Q \tag{13}$$

- We calculate the matrices H_I and H_Q as follows

$$H_I = [I^P, I^{P-1}, \dots, 1] \tag{14}$$

$$H_Q = [Q^P, Q^{P-1}, \dots, 1] \tag{15}$$

- We calculate the matrices M_I and M_Q according to the following

$$M_I = H_I^T.H_I \tag{16}$$

$$M_Q = H_Q^T.H_Q \tag{17}$$

- We calculate the coefficients of the polynomial according to the following relationship

$$A = [a_0, a_1, \dots, a_P]^T = {M_I}^{-1}\left({H_I}^T U_I\right) \tag{18}$$

$$B = [b_0, b_1, \dots, b_P]^T = {M_Q}^{-1}\left({H_Q}^T U_Q\right) \tag{19}$$

- Finally, the signal that has a better EVM can be obtained by

$$y'_{inf} = I'_{inf} + jQ'_{inf} = \left[f^{-1}_{R_I} + \sum_{i=0}^{P} a_i I^i\right] + j\left[f^{-1}_{R_I} + \sum_{i=0}^{P} b_i Q^i\right] \tag{20}$$

IV. Simulation results

The simulations are run in a Gaussian channel. The configuration is performed by using 256 subcarriers, the sampling frequency is 50 MHz, the duration of the guard interval taken equal to $0.8s$, i.e. 40 samples, the number of active subcarriers is 192, and consequently the occupied band is 37.5 MHz. The choice of the number of users depends on the length of the spreading codes used. In our case, we will consider orthogonal Walsh-Hadamard sequences. Indeed, the best properties of this family of codes have been demonstrated in the case of synchronous downlinks. The length L_c of these orthogonal sequences being in power of 2, we will consider in the case where L_c can take the value 16. Thus, each of the considered users can, according to the case, transmit 12 data per MC-CDMA symbol, the spacing between subcarriers is 195.3125 kHz.

As can be observed in Figure5 that the proposed method reduces the PAPR considerably after the first iteration, $N_{iter} = 2$. It can also be noticed that a gain of 6 dB at CCDF = 10^{-3} is obtained between the original OFDM signal (without PAPR reduction) and the IICM method with three iterations $N_{iter} = 3$.

To insure fair comparaison between the two methods in terms of EVM, it should have the same PAPR for both methouds. Figure 6 shows that the two compared method (Clipping and IICM) can have the same PAPR value equale to $9dB$ at CCDF=10^{-3}. The parameter to have this same PAPR value is, $N_{iter} = 2$ for IICM and $A = 0.21$ for conventional clipping.

For the same PAPR, Figure 7 present the EVM of the compared methods. We can see, IICM outperform conventional clipping by 0.06% at IBO=1dB. While, when setting the IBO

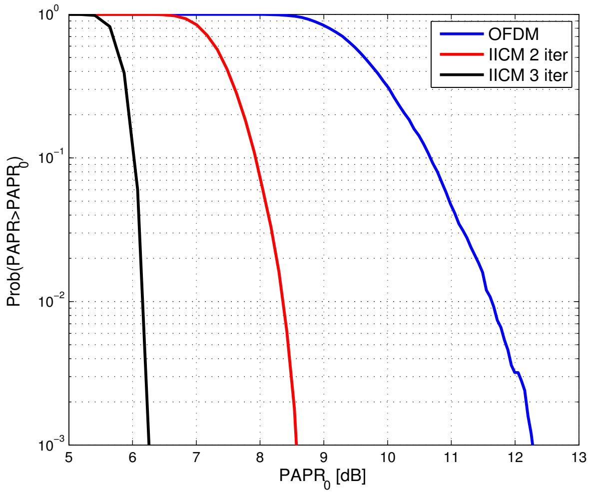

Fig. 5: PAPR reduction performance of the IICM methods for 2 iterations and 3 iterations

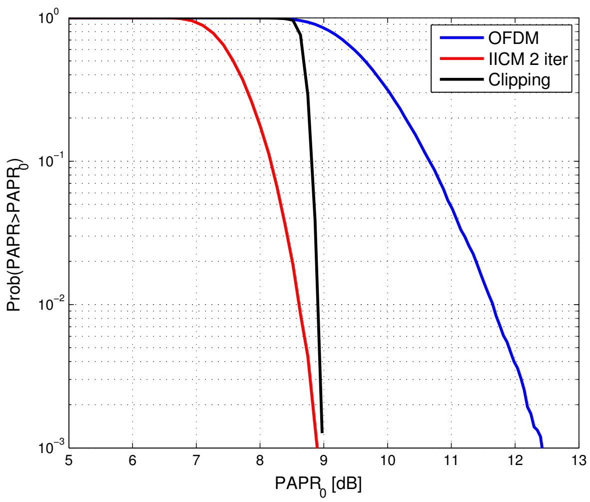

Fig. 6: Comparison of the PAPR reduction performance of the IICM methods, Clipping and the original OFDM signal

of the HPA used for IICM to $IBO_{clp} - 1$, we can see that the two methods have the same EVM, it is to say that there is a gain of 1dB between the two methods.

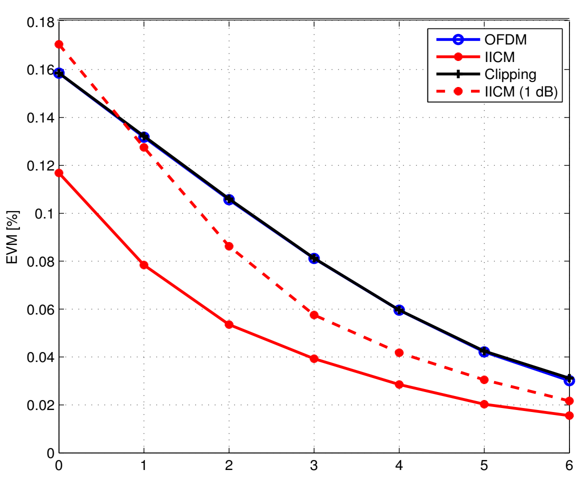

Fig. 7: Comapraison of the EVM of IICM, IICM 1dB, Clip-

V. Conclusion

In this paper we have presented a new PAPR reduction technique for OFDM signals that have strong amplitude fluctuations in a context of nonlinear amplification of these signals. This new technique relies on iterative invertible clipping based on more digital filtering (IFFT/FFT) in transmit before the power amplifier and on the inversion of this clipping function in receive. This allows us to mask the non-linearity of the HPA by that of the clipping in terms of PAPR reduction. Then, we campared the IICM method to conventional clipping in terms of EVM for the same PAPR reduction. The results shows that there is a gain of $1dB$ between the two methods, which is very important in point of view energy efficiency.

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