Invertible Clipping for Increasing the Power Efficiency of OFDM Amplification

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Abstract— **Large fluctuations of OFDM signal amplitude represent an important problem for power amplification in mobile communication systems. In this paper, we propose a new Peak-to-Average Power Ratio (PAPR) reduction method based on the well known clipping and filtering one. Called "invertible clipping", it is performed thanks to a "soft clipping function". Since this soft clipping can be inverted in reception side, degradations are compensated. The derived method benefits from the advantages of classical clipping and filtering method and exhibits small computational complexity as compared to other peak reduction methods. In this paper, we show, thanks to extensive simulation results, that our method offers a global gain, greater than 1 dB. That means that the power efficiency of the Power Amplifier (PA) increases of about 3.2% which corresponds to a PA consumption gain of about 10%.**

I. Introduction

Multi-carrier transmissions and multiple access techniques including OFDM [1], BFDM [5] and MC-CDMA [4], have been receiving a widespread interest for wireless broad-band multimedia applications. Despite their popularity, these techniques have a major drawback, which is their high PAPR that results from the summation of multiple carriers with random phases.

This property has two consequences when these signals go through non-linear devices: first, an increase of the equivalent noise in the signal band, and second, an increase of the out of band signal power (the well-known spectral shoulders).

The problem of power amplification in multi-carrier systems is not new, but it still has not found a satisfactory solution and remains an important research problem. The most common approach today is to sufficiently back off the PA so that it operates in its linear region, which is far below the saturation point. This results in a significant amount of energy loss, generation of high temperatures due to the large power supply, and other disadvantages.

While this approach was acceptable for 2G systems, it is inappropriate for 3G and 4G systems, where power efficiency is a critical issue. Therefore, the problem of non-linear amplification in multi-carrier systems is of major importance. Non-linear PA problems are encountered in most communication systems, including microwave links, satellite communication systems, radio-over-fiber links, magnetic recording devices and mobile communications. As pointed out earlier, the back off solution is usually adopted, but this approach is not satisfactory for future systems.

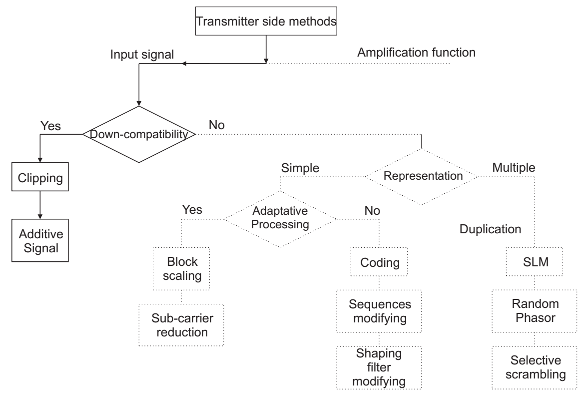

Fig. 1. Possible methods to carry out PAPR reduction

Since decades, many solutions have been proposed to solve this problem. Some of them compensate for non-linearities at the transmitter side and some of them carry out the processing at the receiver side. In this paper, we focus our attention on the transmitter side. As represented in Fig. 1 we have first to distinguish between processing on the amplification function and processing on the signal itself.

Here we are interested in working on the signal itself. Another very important criteria employed to classify methods is the down-compatibility, i.e. methods which do not modify the baseband signal and those which modify it. Among the techniques which modify the baseband signal, we can find Selective Mapping (SLM) [2], Reed-Muller channel coding [3], Partial Transmit Sequences (PTS) [8], etc... . Nevertheless, they have a high computational complexity as major drawback.

There are only a few techniques which are down-compatibles. Among them we find clipping with filtering [7] and tone reservation [11]. This clipping technique is very simple to implement, but it requires a low Clipping Ratio (CR) to achieve a significant PAPR reduction. As a consequence, non-linear problems come out again. Out of band problems are eliminated by filtering, but the in band noise deteriorates the Bit Error Rate (BER). The down-compatibility property is ensured only when the increase of BER due to clipping is small [9].

In this paper, we show that it is possible to increase the power efficiency of the PA when it is used with OFDM signals. To derive this method, we start from the very simple technique previously cited (the "Clipping and Filtering" method) with which we associate an old one, well known in the automatic domain [10]. This method is illustrated in Fig. 2, and it could be summarized by stating that it is always possible to hide a non-linear function with another one which is invertible. We use an appropriate soft clipping function, which is invertible in the definition domain. This is the starting point of our "invertible clipping" method.

The paper is organized as follows: in section II, we describe our technique, the invertible clipping, then in section III simulation results are provided, using the OFDM IEEE 802.11a example [6]. This section is divided in two subsections that show results without and with Additive White Gaussian Noise (AWGN). In section IV, the results prove that the overall system gain, from the amplifier point of view, can reach an Input Back-Off (IBO) of 1 dB. Finally, in section V we give some conclusions to this work.

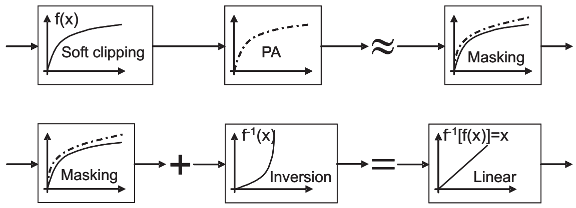

Fig. 2. PA masking and invertible clipping principle

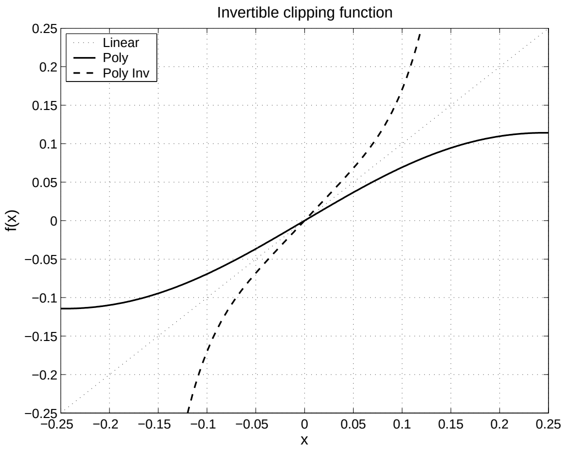

Fig. 3. Invertible clipping function (polynomial) and its inverse

II. Invertible Clipping

A. Principle

The clipping function before non-linear amplification reduces the power dynamics (i.e. PAPR) of the output signal. It works as a sort of masking to the PA's non-linear characteristic. What will be done is to hide the amplifier's non-linear characteristic by a more severe one in term of non linear distortions.

The principle of our new clipping method is derived from the classical clipping. Unlike the classical one, the non-linear clipping function (soft clipping function) is inverted in reception. This allows to compensate the non-linear distortions introduced in the clipped signal's useful band, thus improving the received signal's quality and BER performance.

Therefore, for the same clipping threshold and Eb/No=10 dB, BER due to the classical clipping method is equal to $4.19 \cdot 10^{-1}$ while BER for the invertible clipping one is equal to $1.57 \cdot 10^{-2}$.

Fig. 2 shows PA masking and the principle of the soft invertible clipping. Thus, our proposed method is based on:

- *Soft clipping function* which is a stronger non-linear function than the PA's one and it is placed on the transmitter side. This function should be invertible in the definition domain of the transmitted signal.
- *Filtering function* to obtain the required Adjacent Channel Power Ratio (ACPR) value. This filter does not increase the complexity because in practice it will be performed by a shaping channel filter of IEEE 802.11a OFDM modulation.
- *Inverse non-linear function* on the receiver side.

Given the signal $x(t)$ to be clipped, clipping is carried out through a saturation function $y = f_P(x)$ that has a certain saturation level y_{sat} for which $x(t) = x_{sat}$. The considered function $f_P(.)$ has to be increasing monotone and positive in the $x(t)$ domain.

f_P has been chosen as a polynomial function for the invertible clipping method (see Fig. 3). It is an odd function of fifth order because the even order InterModulation products (IMn), generated by an even polynomial order, are eliminated by the filter and those greater that order $n = 5$, are very small in amplitude. The $\{a_i\}$ coefficients of f_P are calculated to achieve the clipping (saturation) threshold y_{sat} for a Clipping Ratio (CR) equivalent value. The inverted function f_P^{-1} is deduced from f_P. In Fig. 3 its characteristic $f_P(x) = a_1x + a_3x^3 + a_5x^5$ is shown.

The CR is defined as the ratio in voltage between the saturation level (y_{sat}) and the OFDM signal's mean square value (V_{rms}^{ofdm}):

$$CR = \frac{y_{sat}}{V_{rms}^{ofdm}} \tag{1}$$

The IBO represents the input power gap between the mean power of the signal that has to be amplified (P_m^{in}) and the amplifier's saturation power (P_{sat}^{in}):

$$IBO\ [dB] = P_{sat}^{in}\ [dBm] - P_m^{in}\ [dBm] \tag{2}$$

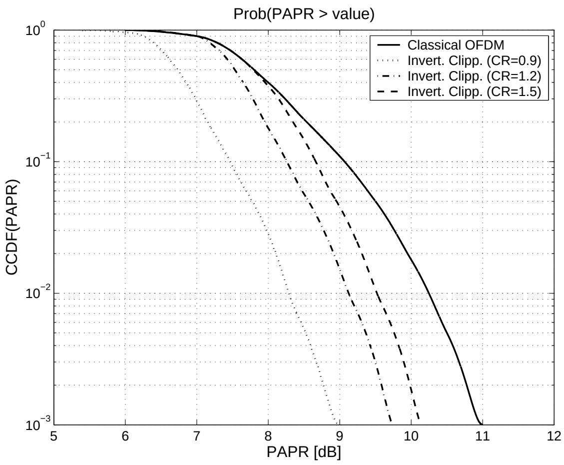

Fig. 4. CCDF of the PAPR

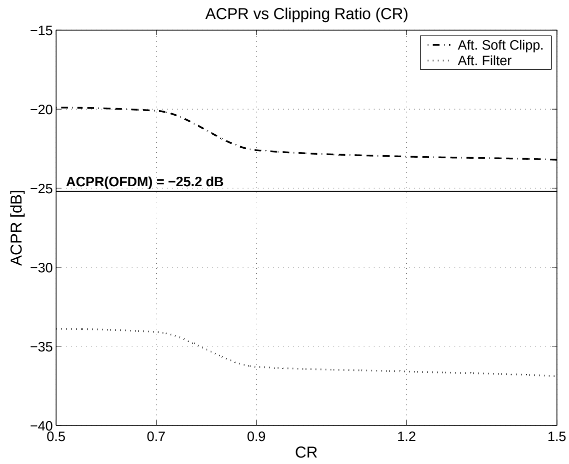

Fig. 5. ACPR versus CR

B. *Effects on signals*

At the transmitter side, the invertible clipping method reduces the amplitude dynamics, and thus the PAPR of the signal that has to be amplified. This result is presented in Complementary Cumulative Distribution Function (CCDF) terms which is defined as follows:

$$CCDF_{PAPR}(papr) = Prob[PAPR > papr] \qquad (3)$$

This function represents the probability that the PAPR of the OFDM signal exceeds the threshold *papr*.

This invertible clipping method allows to reduce the PAPR of the OFDM signal. Fig. 4 shows PAPR's CCDF for classical OFDM signal and for clipped signal using different values of CR = [0.9, 1.2, 1.5]. Here the CCDF of PAPR after clipping decreases slowly, compared to the classical clipping because the invertible clipping function reaches more slowly the saturation level. Thus, PAPR reduction for a CCDF value of 10^{-2} is equal to 2.0, 1.5 and 1.0 dB for a CR value of 0.9, 1.2 and 1.5 respectively. The gain of invertible clipping for a CR value of 0.9 is equivalent to the gain of classical clipping for a CR value of 1.5.

Unfortunately, clipping generates a spectral regrowth (the so called spectral shoulders) on the spectrum of output signal, widening its frequency support. Thus, parasitic frequencies appear in the adjacent channels. Filtering after clipping is therefore compulsory to limit this spectral regrowth and, finally, to assure a good system performance in ACPR terms.

Fig. 5 shows the ACPR degradation due to high clipping (low CR values). If the clipping ratio increases, the degradation of ACPR diminishes and it tends to the value of OFDM signal's ACPR before clipping (-25.2 dB) without ever reaching it. Unlike classical clipping, even if the clipping function does not saturate the signal anymore, the global non-linear behavior of the invertible clipping function (see Fig. 3) always introduces distortions. This justifies that the asymptote of ACPR is higher than the ACPR value of classical OFDM signal.

In the same figure we find the ACPR trend after filtering. We see also the gain of filtering function. The ACPR reduction filter is a Nyquist filter with a bandwidth of 20 MHz and roll-off factor of 0.35 and it does not increase the complexity of this method. In practice, filtering will be performed by a shaping channel filter of IEEE 802.11a OFDM modulation.

With these first simulation results, the efficiency of invertible clipping and filtering on PAPR and ACPR respectively is evident. Now, we shall validate this PAPR reduction method for a complete transmission chain which includes also the PA.

III. Simulation results with PA

In this section we present BER performance of a general transmission system with an invertible clipping, a PA and an AWGN channel. Simulation results have been obtained for an OFDM system based on the IEEE 802.11a standard. The mapping employed is a 16-QAM and the number of sub-carriers is equal to 64 with a signal bandwidth of 20 MHz. The results are given for the three following measurements: ACPR, BER and Error Vector Magnitude (EVM), with a complete chain which includes the PA.

A. *ACPR results with PA without AWGN channel*

Fig. 6 shows that for clipping ratio values from 1.5 to 0.9, there are 3 dB gain on the PA's IBO for the same ACPR value (-29 dB). This may also be interpreted as a much more linear behavior of the PA.

B. *BER with PA and without AWGN channel*

In reception, after inversion and in presence of a noiseless channel, we measure the system performances for BER. Fig. 7 shows the achieved gain. Thus, for CR=0.9 and IBO=3 dB (high clipping zone in the figure), the BER decreases from 10^{-3} to 10^{-5}. It is evident that the PA is hidden by soft clipping in this area. On the contrary, for a CR=1.5 (low clipping zone in the figure) the BER degradation is mainly due to the PA.

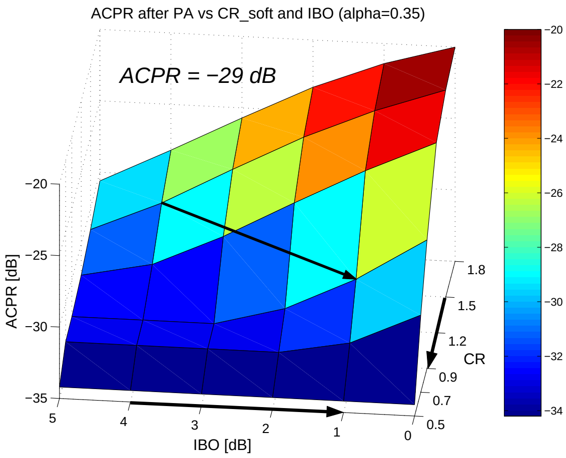

Fig. 6. Gain of 3 dB on the PA's IBO

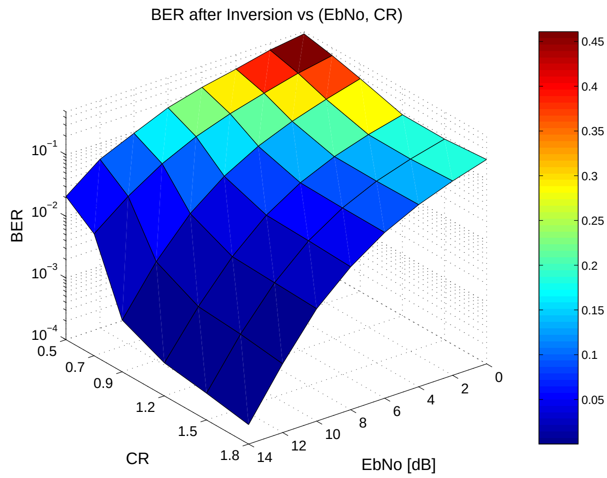

Fig. 8. BER after inversion on the noise channel

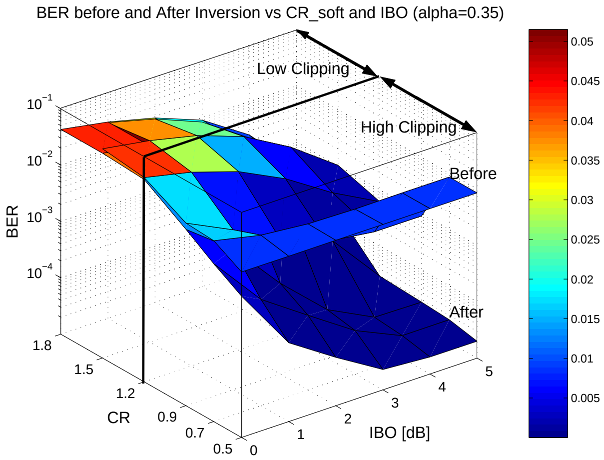

Fig. 7. Inversion effects on BER

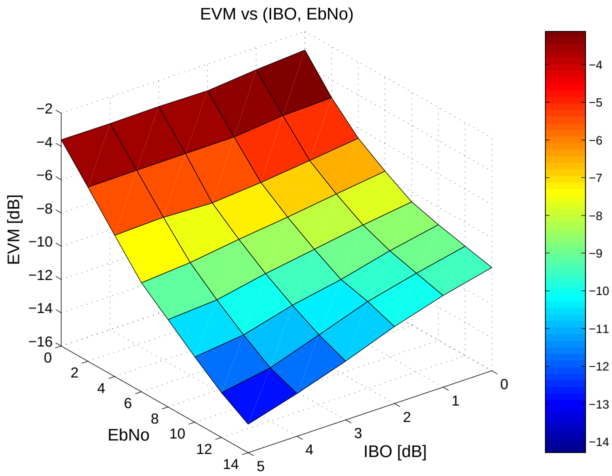

Fig. 9. EVM measurement versus IBO and Eb/No

C. BER and EVM results with AWGN channel

Fig. 8 shows BER after inversion versus CR and Eb/No. Inverse function degrades BER performance of the system because it expands the channel additive noise. Thus, the BER value is of $1.57 \cdot 10^{-2}$ for CR=0.9 and Eb/No=10 dB.

Fig. 9 shows EVM versus IBO and the signal to noise ratio Eb/No. The invertible clipping function and its inverse have not been taken into account. An EVM improvement is obtained for high values of IBO and Eb/No (EVM=−14.3 dB). In this region, the PA becomes more and more linear and the noise power density decreases.

Then, for low values of IBO and Eb/No, a high EVM degradation appears because the PA saturates the OFDM signal and noise power density of the channel becomes important (EVM=−3.1 dB).

IV. Global Performances

The transmission system is composed of several functional blocks: soft polynomial clipping, filtering, PA, noise transmission channel, and inversion. Each of these blocks influences the global system with a positive or negative impact on its performances.

Now, we will determine IBO gain of the PA due to the presence of an invertible clipping system, which represents the main goal in this study. The invertible clipping reduces the amplitude dynamics of the OFDM signal realizing a PAPR reduction. Consequently, this allows to achieve an IBO gain. Moreover the inversion of clipping function improves the quality of the received signal, thus the BER system performance.

Unfortunately, the noise channel will degrade the performances of this new clipping method [§ III-C]. On the receiver side, the inverse function expands the channel additive noise.

Thus, IBO gain analysis will be performed for a global transmission system in presence of a noise channel approaching a realistic transmission context.

The PAPR reduction due to the invertible clipping has already been shown in Fig. 4. A reduction of 2 dB is obtained for a clipping ratio of 0.9 and a CCDF value equal to 10^{-2}. This confirms the efficiency of the new clipping method to

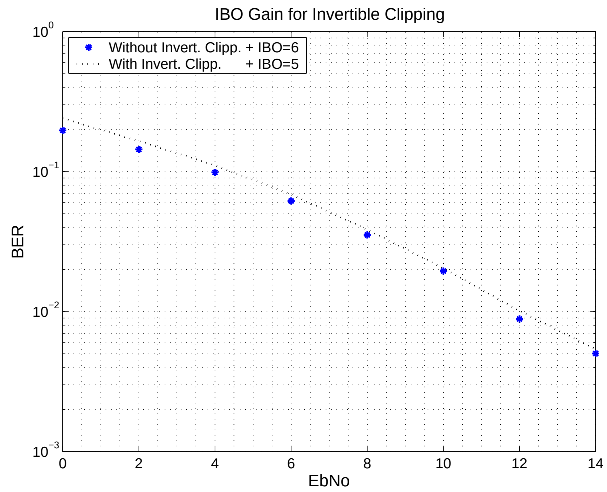

Fig. 10. Real IBO gain due to the invertible clipping

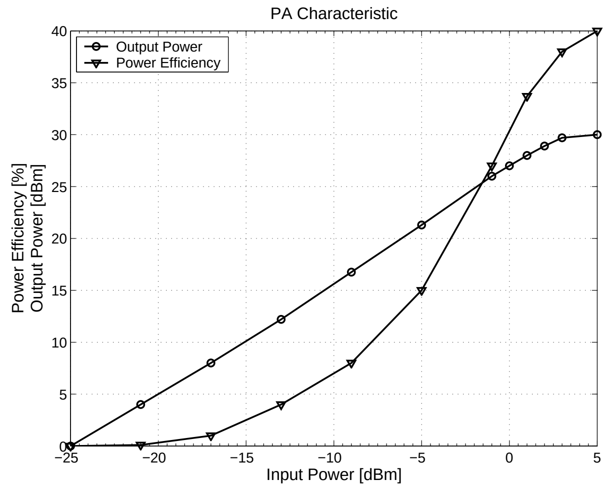

Fig. 11. Power amplifier characteristic (output power and efficiency)

reduce amplitude fluctuations of OFDM signals.

To achieve IBO gain of the PA, the BER is measured versus Eb/No for an IBO value of 6 dB (the system includes the filter, the PA and the AWGN channel). Then, a simulation of the global system (soft clipping, filter, PA, AWGN channel and inversion) allows to calculate the BER versus Eb/No for CR and IBO values of 0.9 and 5 dB respectively (see Fig. 10).

Thus, Fig. 10 shows two BER measurements: without invertible clipping system and IBO=6 dB, and with invertible clipping system and IBO=5 dB. The two curves are the same. After this result we can affirm that the invertible clipping system permits to gain 1 dB on IBO of the PA.

This IBO reduction has an impact on the power efficiency of the PA: from Fig. 11 (which is a typical example of a class AB PA for wireless applications), with a IBO gain of 1 dB, the efficiency grows from 23.8% to 27%, which represents about 10% saving on the PA consumption.

V. Conclusions

The invertible clipping method assures a PAPR reduction keeping a high quality of the received signal thanks to the clipping function inversion. This technique is very simple to carry out. Unfortunately, ACPR raises in consequence of the non-linearities of the clipping function on the transmitter side, thus filtering is necessary in any case. The finality is a power consumption gain of the PA, and in our case we get about 10%, which is considerable for embedded terminals. Further works will deal with the influences of a multi-path fading channel.

References

[1] M. Alard and R. Lassalle, "Principles of modulation and channel coding for digital broadcasting for mobile receivers," in *EBU Review.*, No. 224, Aug. 1987.

[2] R. Bäuml, R. Fischer, J. Huber, "Reducing the Peak-to-Average power Ratio of Multicarrier Modulation by Selecting Mapping", *Electronics Letters*, vol. 32, No. 22, pp. 2056-2057, Oct. 1996.

[3] J.A. Davis, J. Jedwab, "Peak-to-mean power control in OFDM, Golay complementary sequences and Reed-Muller codes", *IEEE Trans. On Inform. Theory*, vol. 45, No. 7, pp. 2397-2417, Nov. 99.

[4] M. Helard, R. Le Gouable, J.F. Helard, and J.-Y. Baudais, "Multicarrier CDMA Techniques for Future Wideband Wireless Networks," in *Annals of Telecomm.*, p.56, n°5-6, May/June 2001.

[5] C. Siclet, P. Siohan and D. Pinchon, "Oversampled orthogonal and biorthogonal multicarrier modulations with perfect reconstruction," in *DSP '00*, Santorini, Jul. 2002.

[6] Institute of Electrical and Electronics Engineers, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications; High-speed Physical Layer in the 5 GHz band", *IEEE Std 802.11*, 1999.

[7] X. Li and L. J. Cimini, "Effects of clipping and filtering on the performance of OFDM", *Proceedings of VTC'97*, 1997.

[8] S. H. Muller, J. B. Huber, "OFDM with reduced Peak-toAverage Power Ratio by Optimum Combinaison of Partial Transmit Sequences", *Electronics Letters*, vol. 33, No. 5, pp. 368-369, Feb. 1997.

[9] H. Ochiai, H. Imai, "Performance Analysis of Deliberately Clipped OFDM Signals", *IEEE Trans. On Comm.*, vol. 50, No. 1, Jan. 2002.

[10] Y. Quénec'hdu, D. Viault, *Systèmes non-linéaires*, Supelec, 2000.

[11] J. Téllado-Mourelo, *Peak to average power reduction for multicarrier modulation*. Ph.D. Report, Stanford University, Sept. 1999.