Design of Crest Factor Reduction Techniques Based on Clipping and Filtering for Wireless Communications Systems

Pedro F. G. da Silva[1], Eduardo G. de Lima[1]

[1]Departamento de Engenharia Elétrica, Universidade Federal do Paraná (UFPR)
Centro Politécnico, CP.19011, CEP 81531-980, Jardim das Américas, Curitiba (PR), Brazil

***Abstract*—Crest factor reduction (CFR) is a technique that is commonly used for the linearization of power amplifiers (PAs) for mobile communication systems. In published works containing the use of CFR, it is assumed *a priori* that the inclusion of CFR will be beneficial, and the main objective is to achieve improvements in the processes of parameter identification or technique implementation. The main contribution of this work is to consolidate a criterion to determine whether is positive or not to linearize a PA through the use of CFR based on a hard clipping limiter followed by a filter. The criterion is then validated through computational simulations performed on a PA modeled by a Wiener cascade and excited by a 3GPP WCDMA signal having a PAPR of 12 dB. It is verified that, in this example, the criterion indicates that the application of CFR is beneficial, which is confirmed by an increase of 1.8 dB in average output power.**

Keywords—Crest factor reduction, hard limiter, linearization, power amplifier, wireless communication systems.

I. Introduction

To improve spectral efficiency, modern wireless communication systems work with signals having a high PAPR. PAPR means peak-to-average power ratio, the ratio between the average power transmitted and the peak power of the signal [1]. For instance, in 3GPP systems, a high PAPR can be occasioned because the WCDMA signal transmitted in downlink consists of various CDMA signals from diverse users. This high PAPR is undesired, because it implies that the power amplifier (PA) must operate in a wide range of input power levels, hence it will be used in an inefficient manner. The PA is the most important element in the transmission chain, both in terms of linearity and power efficiency [2]. To increase efficiency, it is desired that the average output power be the highest possible, and this becomes a problem due to the high value of PAPR of the transmitted signal. When a linearization scheme is applied, it is possible to operate the PA in its nonlinear region, increasing the efficiency. This makes the study of the association PA with linearizers a subject of high interest in the scientific community.

According to [3], the efficiency of class AB power amplifiers lies between 5-10%, and this value can go up to 3-5 times with adequate linearization techniques. Moreover, about 60% of the consumed power in cellular systems is dissipated as heat in the transmitters of the base-stations [4]. Just overcoming this heat dissipation justifies the interest in increasing the power efficiency.

In this context, techniques for PAPR reduction, also called crest factor reduction (CFR) techniques, are attracting the interest of the microwave researchers. This work addresses the linearization of PAs for mobile communication systems based on a CFR technique provided by a cascade connection of a hard clipping limiter followed by a filter. The purpose of this work is to consolidate a simple criterion to evaluate the effectiveness of this CFR technique, that can be applied prior to the CFR actual implementation.

This work is organized as follows. Section II discusses the state-of-the-art on CFR techniques for PA linearization. Section III presents the theoretical development, which is then validated in Section IV. Finally, Section V summarizes the conclusions of this work.

II. State-of-the-art on CFR Techniques for PA Linearization

The goal of the CFR techniques is to reduce the PAPR of a signal. In [5], it was stated that multicarrier signals, like WCDMA and OFDM, have a high PAPR, causing spectral regrowth and in-band distortion when the signal goes through a nonlinear PA.

According to [6], the effectiveness of CFR techniques must be judged by the following factors. First, the technique must significantly reduce PAPR. Second, the power consumption of the proposed algorithm must be low enough in comparison with the increase in PA power efficiency. Other important factors include low implementation complexity, low generation of distortions and little effect on the signal bandwidth.

For mobile communication systems, low computational complexity CFR techniques are the most applicable. In

978-1-4799-1132-5/13/$31.00 ©2013 IEEE

literature, a common way of implementing CFR is by a limiter followed by a filter. These clipping and filtering techniques applicable to mobile communication systems have been proposed by many authors [7], [8]. The main differences among these techniques are the kind of limiter used and the type of filter, as well as the attention given to avoid peak reconstruction after clipping.

In [8], an analysis of the trade-off between the PAPR reduction and in-band and out-of-band distortions was made. It was stated that CFR removes energy from the peaks of the signal at the same time it adds noise inside and outside the signal bandwidth. The in-band noise causes SNR (signal-to-noise ratio) degradation, as well as in-band distortion degradation. The noise outside the signal bandwidth degradates the out-of-band distortion metric, and that needs to be kept inside regulatory limits. In a recent work, it was stated that the success of CFR depends on the availability of margin and that CFR trades off in-band or out-of-band distortions for PAPR reduction [9].

An overview of different CFR techniques and their applications and implementations can be found in [6], [10].

III. THEORETICAL DEVELOPMENT

In this work, only the clipping and filtering CFR technique is considered. The application of clipping and filtering can be commonly found in literature [6], [8]. The block diagram of this technique is shown in Fig. 1. Observe that it consists of a cascade connection between a hard limiter (a static nonlinearity) followed by a filter (a dynamic linearity). An interesting characteristic of this CFR technique is that it does not depend on previous knowledge of the signal modulation. Furthermore, this technique always adds distortions to the signal, and so it is a distortive type of CFR technique. The clipping and filtering is chosen here because it provides a good compromise between the PAPR reduction and the complexity of implementation.

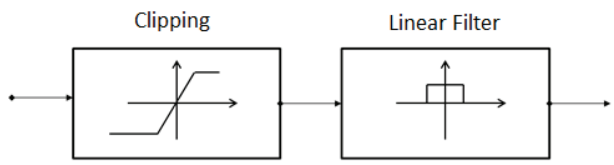


Fig. 1. Block diagram of the clipping and filtering CFR technique.

The objective of this work is to consolidate a criterion that indicates whether is positive to use a CFR technique, composed by a limiter (hard clipping) and a filter, to linearize a PA. The processing of the digital signals throughout the transmission chain must be as linear as possible, a reason why the regulatory agencies demand metrics related to the maximum in-band and out-of-band distortions. Although the calculation and designation of these metrics may vary from signal to signal, the candidate signal to this criterion must have an in-band distortion metric and an out-of-band distortion metric. The principle that guides the CFR as a linearization technique is that the use of the CFR technique may reduce significantly the PAPR of the signal, and hence allowing for the increase of the PA average output power while still satisfying the linearity metrics for in-band and out-of-band distortions. Many papers have been published concerning the use of CFR as a PA linearization strategy, as in [7], [11]. However, in these works, it is established *a priori* that the inclusion of a CFR will be positive, and the contributions of the papers are related to improving the CFR parameter identification or overall implementation.

The criterion is that the linearization of a PA through this CFR technique is beneficial whenever the most critical of the linearization metrics is the out-of-band distortion metric. In other words, the linearization of a PA through this technique is beneficial if, in a situation where the unlinearized PA is being operated at the maximum allowed average output power (i.e. satisfying the linearity metrics imposed by regulatory agencies), the metric for the out-of-band distortion is close to (but slightly below) the regulatory limits, and there is still considerable margin for the in-band distortion metric. This criterion is applicable to various digitally modulated signals (e.g. WCDMA, OFDM) and also to different PAs. It is also noted that this criterion is not always satisfied, as implicitly assumed by previously published works that consider *a priori* that the inclusion of CFR will be positive. Indeed, the fulfillment of this criterion depends on several factors, especially the signal modulation, the distortion metrics and the PA transfer characteristic.

The theoretical justification for this criterion is based on the following reasoning. First, observe that the hard clipping adds some in-band and out-of-band distortions to the signal. However, the filtering action after the clipping is designed to compensate only for the out-of-band distortion, in this way keeping the in-band distortion almost unchanged. Because CFR reduces the PAPR, the inclusion of CFR means that the average input power level may increase but, in the case of clipping and filtering, at the expense of increasing the in-band distortion. Hence, if there is a margin for in-band distortion, the best case scenario for the average output power will be when both distortion metrics reach their respective limits at the same input power level. In this situation, the inclusion of a CFR composed by a hard clipping and filtering will provide an increase on the overall power efficiency of the transmitter.

IV. VALIDATION

In this section, it is reported the computer simulations performed to validate the criterion. The device-under-test (DUT) is a PA behavioral model that represents experimental data measured on a GaN-based PA, operating in class AB and having a center frequency of 900 MHz. The Wiener cascade, composed by a linear finite impulse response (FIR) filter, followed by a static non-linearity (SNL), is chosen for the PA behavioral model.

The signal selected to work with is the WCDMA signal, regulated by the 3GPP standard. In particular, the reported results in this section used the requirements for transmitters and a signal having a PAPR of 12 dB. The in-band distortion measure is the EVM (Error Vector Magnitude), which shows the ratio of the power of the error signal (defined as the difference between distorted and undistorted signals) to the power of the undistorted signal. This value of EVM must be inferior to 17.5%. It is calculated by [1]

$$EVM = \sqrt{\frac{\sum_{n=1}^{N} \left| y_{OUT}(n) - y_{REF}(n) \right|^2}{\sum_{n=1}^{N} \left| y_{REF}(n) \right|^2}} 100\%, \quad (1)$$

where $y_{OUT}(n)$ and $y_{REF}(n)$ are time-domain complex-valued signals at time instant n and N is the number of time samples used in the calculation. Equation (1) computes the EVM of a desired signal $y_{OUT}(n)$ with respect to a reference signal $y_{REF}(n)$.

The out-of-band distortion is evaluated by the ACPR (Adjacent Channel Power Ratio) metric. It shows the ratio between the power in the signal sidebands and the power in the signal bandwidth. ACPR can be calculated by:

$$ACPR = 10\log 10 \left[\frac{\int_{adj} \left| Y_{OUT}(f) \right|^2 df}{\int_{ch} \left| Y_{OUT}(f) \right|^2 df} \right], \quad (2)$$

where $Y_{OUT}(f)$ is the discrete Fourier transform of the signal at the PA output. The integral in the denominator is over the main channel, while the integral in the numerator is over an upper or lower adjacent channel of same bandwidth as the main channel. According to 3GPP specifications, for a bandwidth of 3.84 MHz and for a 5 MHz separation between the center frequencies of the adjacent and main channels, the ACPR cannot exceed -45 dB.

Now attention is turned to Matlab implementation of the CFR linearizer, represented by the block diagram shown in Fig. 1. With respect to the first block of the CFR, it was implemented in MATLAB only the hard clipping amplitude limiter, according to:

$$\begin{cases} X_j = X_i, \text{if} \left| X_i \right| \le F \\ X_j = F \exp\left(j\theta_{X_i} \right), \text{if} \left| X_i \right| > F \end{cases} \quad (3)$$

where F is the clipping factor, Xj is the signal at the output of the limiter, Xi is the signal at the input of the limiter, |.| gives the amplitude of a signal and θ_{Xi} is the phase of the input signal. According to (3), the amplitude of the signal Xj will be equal to the amplitude of Xi, whenever $|Xi|$ is lower than F. Otherwise, $|Xj|$ will be equal to F.

To implement the filter presented in the CFR block diagram shown in Fig. 1, a digital FIR filter is designed. The purpose of this filter is to restore the ACPR to its value before the clipping action. This is achieved here by designing the FIR filter to let the in-band spectrum pass unchanged through the filter, and to replace the out-of-band spectrum of the clipped signal with the out-of-band spectrum of the signal prior to the clipping action.

Several simulations were performed in Matlab. Section IV.A includes the simulation results for the unlinearized PA, while Section IV.B reports the simulation results for the PA linearized by the CFR algorithm. In both cases, a major concern is to obtain the maximum value of average power at the PA output that still satisfies the linearization metrics imposed by 3GPP specifications.

A. Unlinearized PA

In this case, only one design parameter is available: the input power level, which is controlled by a normalized gain (G). The unlinearized PA is simulated for different values of G, starting from a low value. In each simulation, the ACPR and EVM at the PA output are calculated, and the gain is incremented until one or both linearization metrics reach their limits. For instance, with G=0.285 the values of EVM and ACPR are 2.63% and -45.2 dB, respectively, as reported in Table 1. This means that, for the application of the unlinearized PA under test in 3GPP systems, the maximum values of normalized gain and average output power are equal to 0.285 and 11.60 dBm, respectively. Observe that, while the out-of-band distortion quickly reaches its limit of -45 dB, at the maximum normalized gain there is still a large margin in the in-band distortion metric, since its allowed limit is 17.5%. These results indicate that, according to the criterion, the linearization of the PA under test by a CFR is beneficial, once the CFR will reduce the PAPR at the same time it will bring the in-band distortion metric closer to its limit, in this way allowing for an increase in the normalized gain and average output power.

B. PA linearized by CFR

Now, two design parameters are available: the input power level, which is controlled by a normalized gain (G) and the clipping threshold level, which is controlled by the limiter factor F. Lower values of F produce larger signal clipping.

The cascade system composed by a CFR followed by a PA is simulated for different values of F and G. The compromise between the values of F and G is as follows. First, the value of F is set to a high value, larger than the maximum amplitude of the input signal (e.g. no signal clipping, in this case F=1), and the value of G is set to G=0.285, e.g. the maximum value obtained for the unlinearized PA. Then, the value of F is slightly reduced. After that, the value of G is incremented until one or both linearization metrics reach their limits. For higher values of F (none or little signal clipping), it is expected that the out-of-band distortion quickly reaches its limit of -45 dB, while there is still considerable margin in the in-band distortion metric. As the signal clipping becomes larger (the value of F is reduced), the margin in the in-band signal reduces. So, this procedure must be repeated until it is found a particular choice of values for F and G, in which case both distortion metrics reach their respective limits at the same time. Applying this procedure in this example, it is found F=0.545 and G=0.375, as reported in Table 2. Observe that, for these values of F and G, EVM and ACPR are at the edge of their specifications and the PA under test can be used for

3GPP systems with a normalized average output power of 13.40 dBm. In other words, observe that using the CFR as a linearizer for the PA under test, it is possible to increase the average output power by 1.8 dB, in comparison to the unlinearized PA. Such improvement is achieved by reducing the signal PAPR by 2.30 dB and putting the in-band distortion at its upper limit.

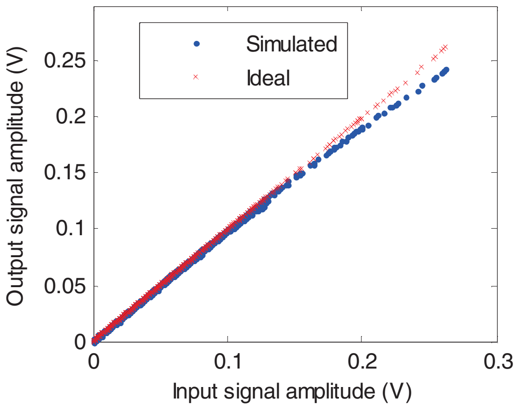
TABLE I. SIMULATION RESULTS FOR THE UNLINEARIZED PA

Parameters	**Results**
G	0.285
EVM	2.63%
ACPR	-45.2 dB
Average output power	11.60 dBm

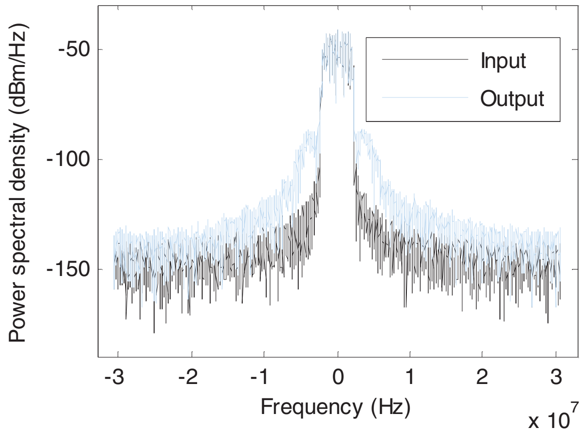
TABLE II. SIMULATION RESULTS FOR THE PA LINEARIZED BY CFR

Parameters	**Results**
F	0.545
G	0.375
EVM	17.40%
ACPR	-45.0 dB
Average output power	13.40 dBm

Finally, for the particular cases reported in Tables 1 and 2, in Fig. 2 is shown the AM-AM conversion and power spectral densities (PSDs) for the unlinearized PA, while in Fig. 3 is shown the AM-AM conversion and PSDs for the linearized PA by the CFR algorithm.

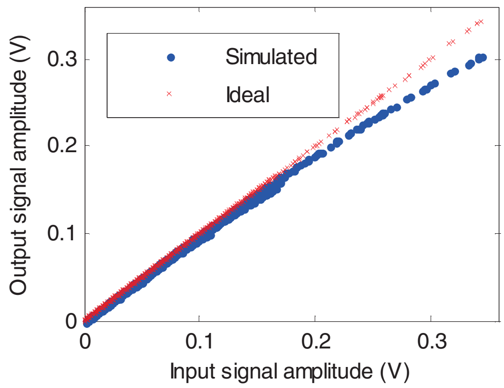


(a)

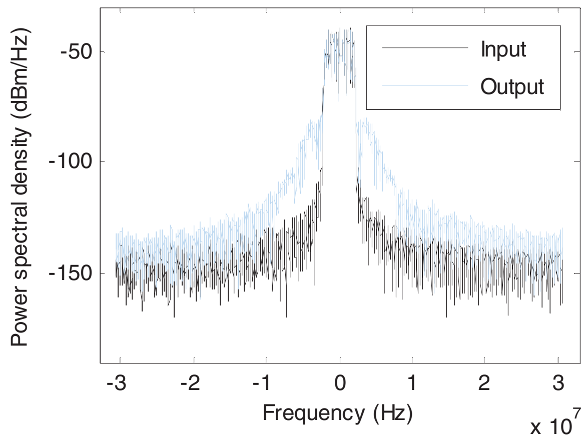


(b)

Fig. 2. Unlinearized PA. a) AM/AM characteristics. (b) PSD plots.



(a)



(b)

Fig. 3. Linearized PA. (a) AM/AM characteristics. (b) PSD plots.

V. CONCLUSION

In this work, the CFR technique for PA linearization for mobile communication systems is discussed. The main contribution of this work is to consolidate a criterion to determine when is positive to linearize a PA through the technique of CFR based on a hard clipping limiter followed by a filter. The criterion is relevant because it allows the designer to identify the effectiveness of this linearization technique before implementing it. The criterion is validated through numerical simulations performed on a PA modeled by a Wiener cascade and excited by a 3GPP WCDMA signal having a PAPR of 12 dB. In this example, it is observed that, without linearization, there is still available margin in in-band metric, thus in accordance to the criterion, it is positive the use of CFR. Moreover, it is obtained an increase of 1.8 dB in average output power through the inclusion of the CFR technique, with respect to the case without linearization, confirming the accuracy of the criterion.

ACKNOWLEDGMENT

The authors would like to thank the financial support provided by Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

REFERENCES

[1] P. Gilabert, A. Cesari, G. Montoro, E. Bertran, J. Dilhac, “Multi-lookup table FPGA implementation of an adaptive digital predistorter for linearizing RF power amplifiers with memory effects”, *IEEE Trans. Microw. Theory Tech.*, vol. 56, n. 2, pp.372-384, Feb. 2008.

[2] J. Pedro, S. Maas, “A comparative overview of microwave and wireless power-amplifier behavioral modeling approaches”, *IEEE Trans. Microw. Theory Tech.*, vol. 53, n. 4, pp. 1150-1163, April 2005.

[3] H. Gandhi, “A flexible Volterra-based adaptive digital pre-distortion solution for wideband RF power amplifier linearization”, *Microwaves and RF Magazine*, Jul.-Aug. 2008.

[4] D. Raychaudhuri, N. Mandayam, "Frontiers of wireless and mobile communications", *Proceedings of the IEEE*, vol.100, n..4, pp. 824-840, April 2012.

[5] X. Li, L. Cimini, “Effects of clipping and filtering on the performance of OFDM”, *IEEE Communications Letters*, vol. 2, n. 5, pp. 131-133, May 1998.

[6] L. Wang, C. Tellambura, “An overview of peak-to-average power ratio reduction techniques for OFDM systems”, in *IEEE International Symposium on Signal Processing and Information Technology*, pp. 840-845, 2006.

[7] N. Lashkarian, H. Tarn, C. Dick, “Crest factor reduction in multi-carrier WCDMA transmitters”, in *IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 1, pp. 321-325, 2005.

[8] P. Swaroop, K. Gard, “Crest factor reduction through in-band and out-of-band distortion optimization”, in *IEEE Radio and Wireless Symposium*, pp. 759-762, 2008.

[9] R. N. Braithwaite, “A combined approach to digital predistortion and crest factor reduction for the linearization of an RF power amplifier”, *IEEE Trans. Microw. Theory Tech.*, vol.61, no.1, pp.291-302, Jan. 2013.

[10] T. Jiang, Y. Wu, “An overview: peak-to-average power ratio reduction techniques for OFDM signals”, *IEEE Trans.Broadcast.*, vol. 54, n. 2, pp. 257-268, June 2008.

[11] O. Vaananen, J. Vankka, K. Halonen, “Simple algorithm for peak windowing and its application in GSM, EDGE and WCDMA systems”, *IEE Proceedings Communications*, vol. 152, n. 3, pp. 357-362, June 2005.