Effects of Crest Factor Reduction on the Predistortion Performance for Multi-Carrier 3G RF Power Amplifiers

Oualid Hammi [1,2], Scott Carichner [3], Bill Vassilakis [3], and Fadhel M. Ghannouchi [1]

[1] iRadio Lab., Department of Electrical and Computer Engineering, Schulich School of Engineering, University of Calgary, Calgary, AB, T2N 1N4, Canada

[2] Green Radio Technologies, Inc., Calgary, AB, T2M 2L7, Canada

[3] Powerwave Technologies, Inc., 1801 East St. Andrew Place, Santa Ana, CA, 92705, USA

Abstract — **In this paper, an analysis of the crest factor reduction effects' on the predistortion performance of 3G multi-carrier power amplifiers is carried out. This study is performed at three different levels: the power amplifier level, the digital predistorter level, and the system level (linearized amplifier) for a Doherty amplifier driven by 3-carrier WCDMA signal. At the amplifier level, the use of crest factor reduction results in higher power efficiency, increased output power but also distortions. Experimental results show that this compromises the performance of the digital predistorter. The system level analysis highlighted that, in such case, the gained efficiency at the amplifier level will be lost after linearization. This is the first study that points out and experimentally reports the drawbacks of crest factor reduction when applied to digitally predistorted multi-carrier power amplifiers.**

Index Terms — **3G, crest factor reduction, digital predistortion, PAPR, power amplifier, WCDMA.**

I. Introduction

Radio frequency (RF) power amplifiers (PAs) are one of the most critical and expensive subsystems in wireless communication infrastructure. In 3G and 3G+ wireless communication standards, power amplifiers are designed to meet stringent linearity requirements set by regulatory organizations. In addition, since the PA consumes most of the energy in base stations, its power efficiency is a primary concern. In fact, higher efficiency will translate into lower capital and operation expenses at the base station level. However, linearity and power efficiency can not be achieved simultaneously in power amplification systems. Indeed, the efficiency is low when the amplifier is operated in its linear region. Conversely, poor linearity is observed when the amplifier is operated in high efficiency mode. An important design aspect focuses on the trade-off between linearity and efficiency in power amplification systems. However, while linearity is a must, power efficiency is a need. Accordingly, the design methodology focuses on meeting the linearity performance while achieving the highest possible power efficiency. Currently, state of the art technology uses Doherty power amplifiers along with a digital predistortion technique to achieve the required trade-off between linearity and efficiency [1]-[3].

In 3G and 3G+ wireless communication systems, the signals to be transmitted typically result in high varying amplitudes with high peak to average power ratio (PAPR). This is the key parameter that limits the achievable power efficiency for a given amplifier. Indeed, for digital predistortion systems, the maximum average output power and efficiency are those corresponding to an operating output power back-off (OPBO) that is equal to the signal's PAPR. Accordingly, reducing the signal's PAPR can decrease the operating OPBO and consequently increase the output power and efficiency. Several crest factor reduction (CFR) techniques have been reported in the literature. This includes the clipping and filtering technique, the coding technique, the partial transmit sequence technique, the selected mapping technique, etc [4][5]. So far, CFR has been perceived as a complementary technique to digital predistortion. The combination of both leads to the highest possible trade-off in system level performance in terms of linearity and power efficiency [3][6][7].

This paper presents a first study of the effects of crest factor reduction in digital predistortion systems in the context of multi-carrier power amplifiers. The drawbacks of CFR on the system level performance are highlighted through an experimental validation. In Section II, the effects of CFR on the power amplifier performances are discussed. Then, in Section III, an experimental study is carried out to evaluate the consequences of CFR on the digital predistorter performances. In Section IV, a brief system level study of the impacts of CFR is presented. The conclusions are derived in Section V.

II. Crest Factor Reduction Effects' on Power Amplifier Behavior

In power amplifiers design and linearization, the crest factor reduction technique that is widely used is based on clipping and filtering. This technique leads to in-band distortions that increase the error vector magnitude (EVM). This limits the clipping factor that can be used while meeting the standards' requirements for the EVM performance. Typically, for WCDMA applications, a crest factor reduction by 3 to 4 dB, results in an EVM of 8% which is still compliant with the standard requirements (17% for QPSK and 12% for 16QAM in HSPA) and leaves sufficient margin for meeting the EVM specifications at the system level.

Reducing the crest factor of the signal by 3 to 4 dB will ideally result in lowering the operating OPBO of the power amplifier by the same quantity. Such increase in the average output power leads to a power efficiency increase typically between 5% and 10% depending on the type of the PA and the starting efficiency. Figure 1 illustrates the operating conditions of a highly efficient Doherty amplifier driven by a WCDMA input signal before and after crest factor reduction. Here, the WCDMA signal has a PAPR of 10.6 dB before crest factor reduction, and 7.1 dB after crest factor reduction. The probability density function of each of these signals is plotted along with the PA's AM/AM characteristics. This figure clearly shows the effects of the CFR on the nonlinearities that will be exhibited by the PA. Indeed, by applying the crest factor reduction and pushing the operating average power of the amplifier closer to saturation, the high input power levels probability is significantly more important than that observed in the case where there is no CFR. Accordingly, the contributions of high order intermodulations to the behavior of the power amplifier are expected to be considerably higher when the CFR is used in comparison with the case where the CFR is off.

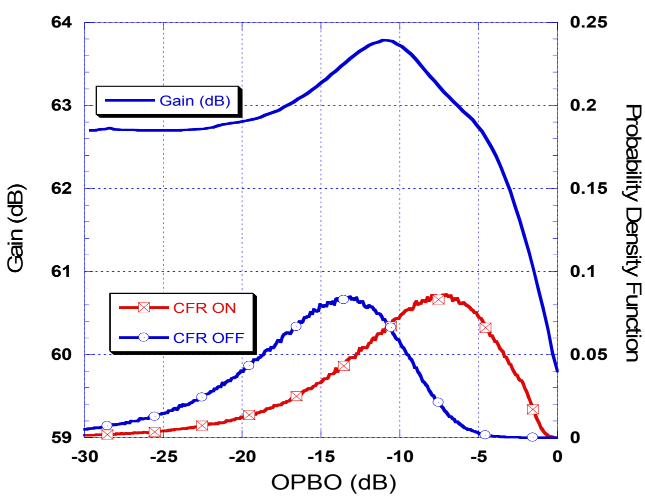

Fig. 1. PA AM/AM Characteristic and signals' pdf.

III. Crest Factor Reduction Effects' on DPD Performance

First, it is worthy to mention here the advantage of the CFR on the SNR and consequently the ACPR of the linearized signal. Indeed, for a given ADC, the SNR can be approximated by [5]:

$$SNR = 6.02N + 4.77 - PAPR + 10\log_{10}(OSR) \quad (1)$$

where N and OSR are the number of bits and the oversampling ratio, respectively.

Accordingly, following the CFR, the SNR of the signal obtained after digitization at the receiver level will be improved by an amount equal to the crest factor reduction as demonstrated by the previous equation and the experimental results reported in Figure 2. Since the quality of the observation path sets an upper limit on the linearity performance that can be achieved after linearization, the observed SNR degradation will affect the DPD performance when the ADC dynamic range is lower than that of the DAC.

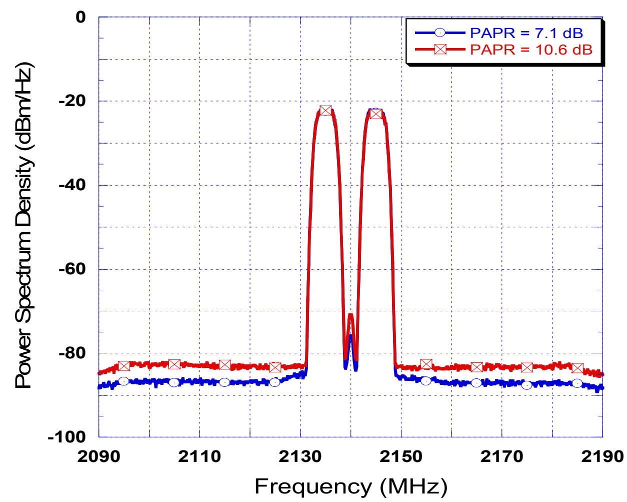

Fig. 2. Measured input spectra with and without CFR.

The device under test, a 300-Watt Doherty power amplifier prototype, was characterized using a 3-carrier WCDMA input signal having a total bandwidth of 15 MHz. First, the amplifier was driven by the original input signal (PAPR = 10.6 dB), and linearized using a standard memory polynomial based digital predistorter. The DPD dimension was set to 12 for the nonlinearity order and 3 for the number of branches. This dimension was verified to be sufficient to model / linearize the device under test. During the characterization step, the PA's output waveform was sampled at a rate of 96 Msps which corresponds to an observation bandwidth of 75 MHz at the receiver level (vector signal analyzer). The measured spectra at the output of the PA before and after linearization are reported in Figure 3 which also shows the spectrum of the input signal. According to this figure, satisfactory linearity performances are obtained with an improvement of the spectrum regrowth over the observation bandwidth. The observed increase in the noise floor is mainly due to the increase in the PAPR of the signal following the digital predistortion process. These results were obtained when the PA was operated at an OPBO equal to the PAPR of the original input signal (OPBO = 10.6 dB).

In the second test, the PA was driven with the signal obtained following the crest factor reduction (PAPR = 7.1 dB). The sampling rate and observation bandwidth, as well as the DPD parameters were set to the same values used with the previous signal. The measurement results are reported in Figure 4. This highlights the limited improvement in the spectrum regrowth when compared to the results reported in Figure 3. To further investigate the origin of such limited DPD performance, a second DPD having a nonlinearity order and a memory depth of 15 and 6 respectively, was applied to linearize the device under test. The spectra measured at the output of the linearized amplifier with this DPD are also reported in Figure 4. Both DPD results were measured when the PA is operated at an OPBO equal to the PAPR of the original input signal (OPBO = 7.1 dB). The linearity performance of both DPD are similar showing that the limited linearity performance are not due to the DPD dimension.

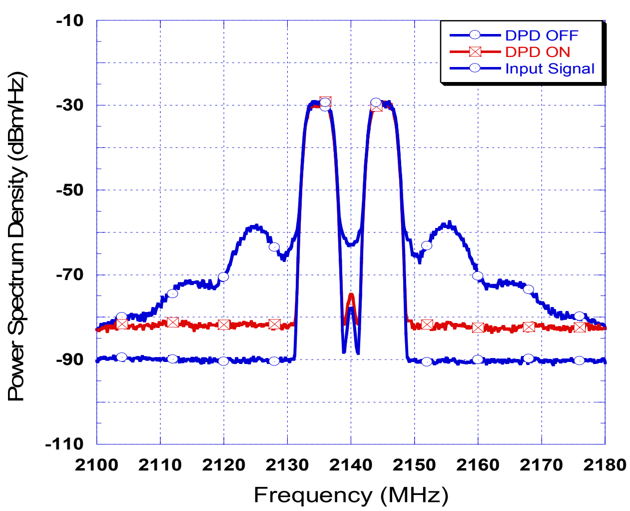

Fig. 3. Measured spectra before and after DPD (CFR OFF).

IV. Discussion and Analysis

The measured DPD results reported in the previous section clearly show that the use of the CFR may compromise the performance of the digital predistortion system in multi-carrier power amplifiers. In fact, when the CFR is ON the power amplifier is operated more into its nonlinear region. In such case, the contribution of high order nonlinearities is important and needs to be accurately measured in order to synthesize the optimal digital predistortion function. Also, these high order intermodulation needs to be accurately synthesized in the predistorted signal. However, and due to the limited bandwidth of the observation / characterization path and that of the signal generation, these high order intermodulation components can not be accurately observed / generated. Also, this lack of linearizability can be attributed to the higher probability of the signal around the Doherty transition point (turn-on of the peaking amplifier at approximately 6 dB OPB). These are the main factor limiting the performance of the digital predistortion results reported in Figure 4.

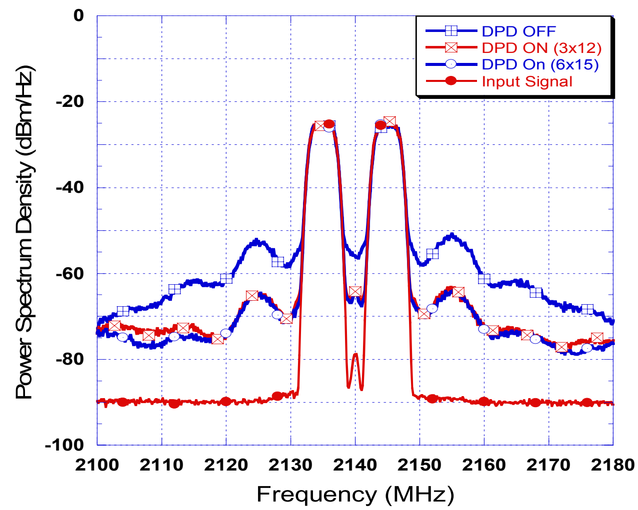

Fig. 4. Measured spectra before and after DPD (CFR ON).

In such cases, where DPD performance fails to meet the linearity requirements either due to hardware or technology related limitations, the only alternative that can be considered in order to meet the linearity requirements while operating the amplifier with the same signal, consists in using feedforward technique. In fact, feedforward technique does not have bandwidths limitations similar to those observed with digital predistortion technique [8]. Moreover, its performances are not affected by the type of nonlinearity (static or dynamic) that is being compensated. However, the use of the feedforward technique will result in a system level power efficiency that is significantly lower than that of the power amplifier mainly due to the power consumption in the auxiliary amplifier that needs to be ultra linear and to have a flat frequency response over the required observation bandwidth. In addition, the use of feedforward will increase the overall cost of the amplification system.

Conversely, if due to the bandwidth restriction, the crest factor reduction was not applied to the input signal, the digital predistortion technique is sufficient to meet the linearity performance required by the wireless communication standard. This will result, at the PA level, in a lower average output power and power efficiency when compared with the case where the crest factor reduction was applied. These parameters are quantified in Table 1. This shows that the output power capabilities are reduced by 3 dB and the drain efficiency is reduced by 8%. Accordingly, a transistor that is two times larger is needed to compensate for this output power reduction. This increase in the cost is compensated by the use of more cost effective linearizer (DPD vs. feedforward). Furthermore, the power efficiency drop can be compensated at the system level by using a predistortion based linearizer rather than a feedforward linearizer. Accordingly, the use of the CFR with multi-carrier power amplifiers presents important drawbacks and an in-depth system level analysis of the cost and efficiency of the power amplification system (PA + linearizer) is needed to evaluate the usefulness of CFR in such context.

IV. Conclusion

In this paper, the effects of crest factor reduction on the performance of multi-carrier power amplifiers are closely examined. First, it was shown that when crest factor reduction is by-passed, digital predistortion technique can achieve satisfactory linearity performance with an observation bandwidth that includes up to the 5^{th} order intermodulation products. Conversely, by operating the amplifier closer to saturation, the use of crest factor reduction limits the linearity performance that can be achieved using digital predistortion technique when the same observation bandwidth is used. Finally, the implications of these results on the system level design of power amplification systems were considered. It was shown that the reduction in cost and the increase of the efficiency that can be achieved at the power amplifier level when a CFR technique is used can be lost at the system level due to the use of a less cost-effective and power efficient linearization technique.

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