Synergetic Crest Factor Reduction and Baseband Digital Predistortion for Adaptive 3G Doherty Power Amplifier Linearizer Design

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***Abstract*—A novel approach for power amplifier (PA) characterization suitable for single iteration digital predistorter synthesis is proposed. This approach consists of synergetic crest factor reduction and baseband digital predistortion to avoid the average power variation at the input of the PA between the characterization and linearization steps. This is achieved by bypassing the crest factor reduction block during the characterization step and by applying it concurrently with digital predistortion in the linearization step. First, the PA's behavior sensitivity to the average input power is evaluated. The limitations of conventional approaches for the PA characterization, in the context of single iteration digital predistortion, are then demonstrated. The performance of the proposed technique is validated experimentally on a 300-W peak PA. The measured improvement of the adjacent channel power ratio at the output of the linearized amplifier is 16 dBc for the conventional approach and 29 dBc for the proposed approach.**

***Index Terms*—Crest factor reduction, digital predistorter (DPD), linearization, peak-to-average power ratio (PAPR), power amplifier (PA), wideband code division multiple access (WCDMA).**

I. Introduction

WIRELESS communication systems, including code division multiple access (CDMA) and orthogonal frequency division multiplexing (OFDM) based standards, involve amplitude modulated signals. In these signals, the crest factor, which is the ratio between the average power of the signal waveform and its peak power, is considerably high and can exceed 10 dB. Such a high crest factor sets severe operating conditions on the RF front end, especially the RF power amplifier (PA). In fact, in addition to the power-efficiency performance that is sought in any wireless communication system, high crest factor signals require highly linear transmitters/PAs.

Linearization techniques, particularly digital predistortion, are being used to meet the linearity requirements, while operating the PA over its entire power range [1]–[5]. In these conditions, and assuming a perfect match between the predistortion function and the PA's nonlinearity, the PA can meet the linearity requirement while operating at an output power backoff (OPBO) equal to the crest factor of the signal. Herein, the OPBO is defined as the back off of the signal's average output power from the amplifier's saturation output power. This often results in relatively low power efficiency in the range of 15%–20%.

In order to be able to drive the PA further into its power-efficient region, crest factor reduction techniques have been proposed [2]–[7]. By reducing the signal's crest factor, these techniques allow the PA to operate closer to saturation at a lower OPBO level, which increases the PA's output power, as well as its power efficiency. Several crest factor reduction techniques have been proposed in the literature, namely, the clipping and filtering technique, coding technique, partial transmit sequence technique, selected mapping technique, interleaving technique, tone reservation technique, tone injection technique, active constellation extension technique, etc. [6]. However, when there is no access to the signal coding and modulation sections, the clipping and filtering technique is the only crest factor reduction technique that can be considered. Accordingly, baseband digital predistortion and crest factor reduction techniques are used to optimize the performance of PAs/transmitters driven by high crest factor signals. However, these two sub-blocks are designed and applied separately and independently of each other [2]–[5].

In this paper, synergetic crest factor reduction and single iteration digital predistortion are proposed to optimize the linearity performance of the RF PA. This consists in controlling the signal's characteristics during the characterization step, in order to guarantee quasi-optimal predistorter performance within a single iteration. The performance of this approach is assessed experimentally and compared to that of conventional systems, where the crest factor reduction and digital predistortion are implemented independently of each other. The sensitivity of the PA's nonlinear characteristics to the driving signal's average power and statistics is quantified in Section II. In Section III, the problem of PA characterization for single iteration digital predistorters (DPDs) is formulated and described. The proposed approach of synergic crest factor reduction and digital predistortion is introduced in Section IV. The experimental validation of the proposed approach is presented in Section V. Conclusions are then presented in Section VI.

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II. Sensitivity of PA's Behavior to Input Signal Characteristics

The device-under-test considered in this study was a 300-W peak power Doherty amplifier, operating around 2140 MHz. This amplifier was driven by a single-carrier wideband CDMA (WCDMA) signal generated according to test model 1 (TM1). The PA was characterized using a typical experimental setup for input and output complex baseband waveform measurements. This setup includes an arbitrary waveform generator and a vector signal analyzer.

A first study of the average power variation effects on the PA behavior from a modeling perspective was presented in [8]. In this study, the sensitivity of the device-under-test to both the statistics of the input signal and its average power is evaluated experimentally. For this purpose, several versions of the original signal were generated by applying a crest factor reduction algorithm to the original WCDMA signal. The crest factor reduction algorithm consists of a limiter followed by a filter. The threshold of the limiter was set to various values. Accordingly, several crest factor reduced versions of the WCDMA signal were generated. The peak-to-average power ratios (PAPRs) of these signals ranged from 10.7 dB, which is the PAPR of the original signal, to 7.1 dB. These signals were then used in two different tests.

In the first test, the various signals were used to characterize the PA up to its input saturation power. This was achieved by adjusting the average power level at the PA's input, depending on the signal's PAPR, so that the maximum input power hits the PA's input saturation power. The characterization results are reported in Fig. 1 for different signals. According to these results, the average power variation at the input of the device-under-test affects its behavior considerably, especially the AM/AM characteristic. Such variation in the AM/AM behavior is not attributed to thermal grounding since the mechanical design of the PA prototype has properly accounted for thermal issues. The dependency of the AM/AM characteristic on the average power of the input signal is expected and is mainly due to the enhancements that were made to the Doherty amplifier prototype to extract extremely high efficiency.

In order to evaluate the effects of the signal statistics on PA behavior, the previously generated WCDMA signals, which had different statistics, were applied to the PA. For this test, the average power of the signals was kept constant. The measurement results presented in Fig. 2 show that the statistics of the signal did not affect either the AM/AM or AM/PM characteristics of the PA. In fact, for the considered signals, the measured PA's nonlinear characteristics were independent of the signal statistics, as long as the average power was not varied.

III. Single Iteration DPDs

The performance of digital predistortion based linearizers is greatly dependant on the perfect match between the predistorter's nonlinear function and the actual nonlinearity of the PA. For this purpose, the PA behavior observed during the characterization step that leads to the synthesis of the predistortion function should be similar, or at least close enough, to the behavior exhibited by the PA when driven by the predistorted signal. This consists in keeping similar PA operating conditions between the characterization and linearization steps, mainly by maintaining the average power, bandwidth, and statistics of the PA's input signal. In fact, as shown in Section II, the behavior of PAs depends on the average input power. Accordingly, the performance of DPDs is affected by the average power variation at the input of the PA between the characterization and linearization steps. A first study of this was reported in [9]. Herein, the PA behavior variations due to aging, temperature, and bias drifts are considered to be long-term variations and are not taken into account.

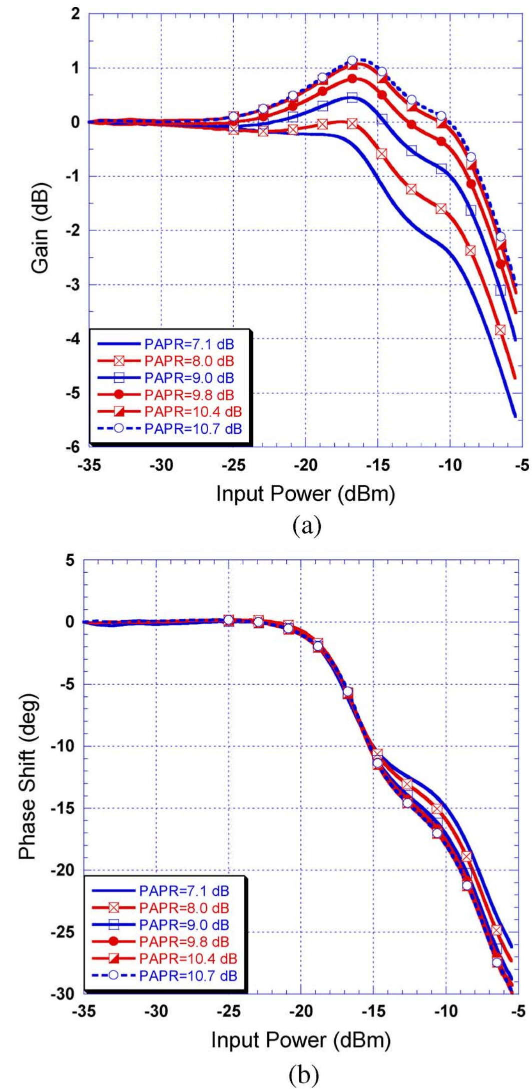

Fig. 1. PA's measured characteristics at various average input power levels. (a) AM/AM characteristics. (b) AM/PM characteristics.

DPDs can be divided into two categories: iterative DPDs and single iteration DPDs. In the first category, whenever an update of the predistortion function is needed, the DPD parameters are identified through several iterations, each of which implies device-under-test characterization, predistortion function synthesis, and application usually by minimizing an error signal [10]. Conversely, in single iteration predistorters, whenever an update of the predistortion function is needed, the DPD parameters are identified within one characterization process [11], [12].

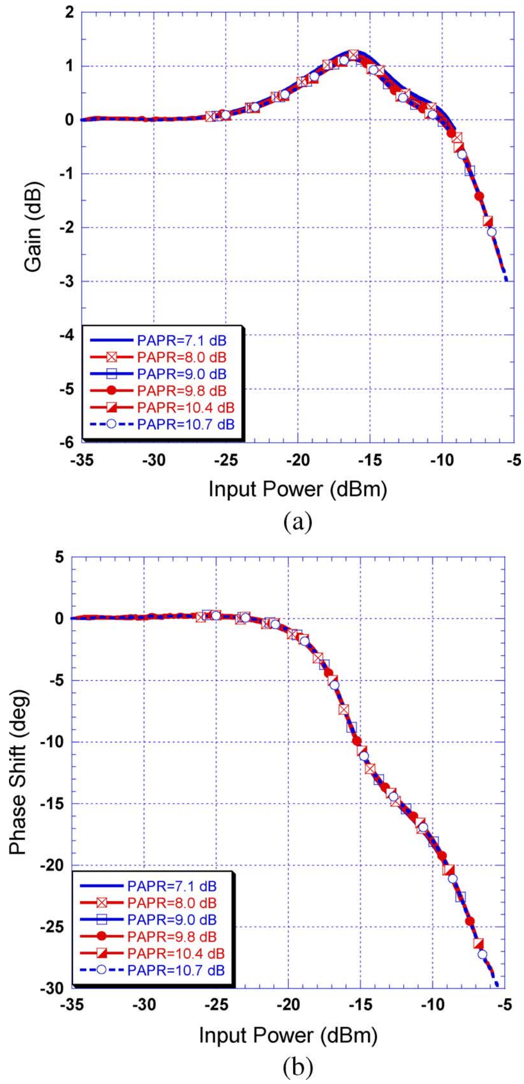

Fig. 2. PA's measured characteristics at constant average input power levels. (a) AM/AM characteristics. (b) AM/PM characteristics.

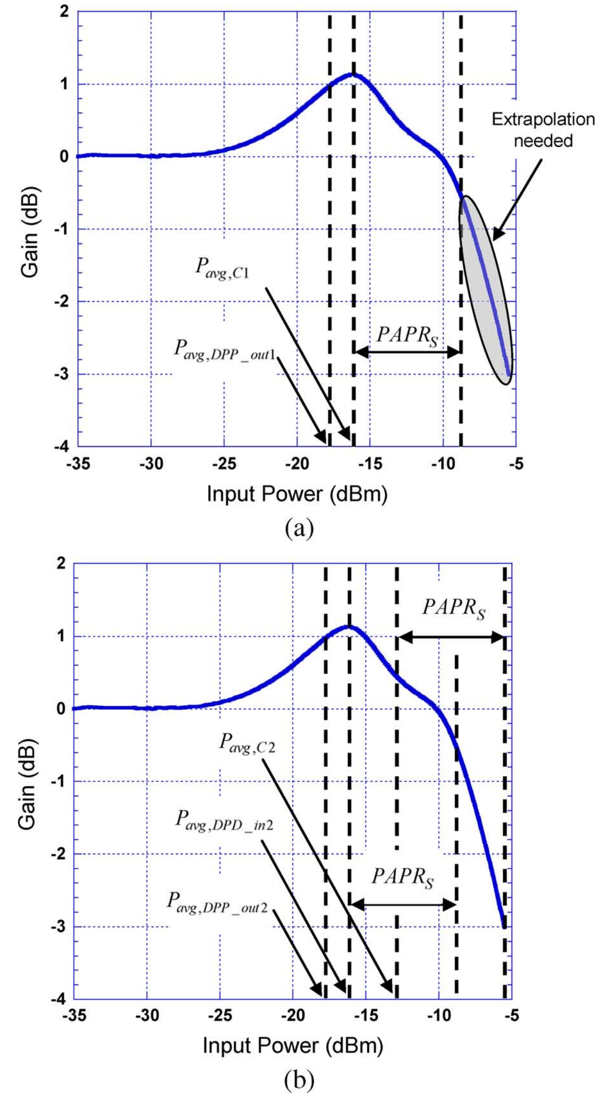

Fig. 3. Power levels at characterization and linearization steps. (a) Constant average power approach. (b) Constant peak power approach.

Accordingly, it is critical to perform the appropriate PA characterization that ensures high linearity performance after linearization when single iteration DPDs are considered. Indeed, in iterative digital predistortion techniques, the mismatch between the DPD's nonlinear characteristics and the actual PA's AM/AM and AM/PM characteristics can be compensated for through the iterations. This paper focuses exclusively on single iteration baseband DPDs. It is worth mentioning that both iterative and noniterative (single iteration) predistorters can be made adaptive or not. This adaptability is usually implemented in a closed-loop configuration for iterative predistorters (e.g., an error signal is continuously derived and used to update the DPD). However, the adoption of a single iteration DPD can alleviate the requirement on the feedback/monitoring loop. The feedback loop is turned on only when linearity performance does not meet a specified target requirement (e.g., spectrum emission mask), and a single characterization is performed and used to derive the DPD parameters.

For a given PA driven by a signal having an average power ($P_{\text{avg},S}$) and a PAPR (PAPR_S), two approaches can be considered for PA characterization and digital predistortion synthesis, as shown in Fig. 3. In the first approach, based on a constant average power, the signal's average power during the characterization step ($P_{\text{avg},C1}$) is kept equal to the average power of the original signal ($P_{\text{avg},S}$). Accordingly, the PA behavior will be captured for instantaneous input power levels up to

$$P_{\text{max},C1} = P_{\text{avg},S} + \text{PAPR}_S. \tag{1}$$

Herein, and unless otherwise specified, all the power, gain, and PAPR values are expressed in decibels. Following this characterization, the maximum admissible power at the input of the derived digital predistortion characteristic is given by

$$P_{\text{max,DPD\_in1}} = P_{\text{max},C1} + G_{\text{PA}}(P_{\text{max},C1}) \tag{2}$$

where $G_{\text{PA}}(P_{\text{max},C1})$ is the normalized gain of the PA at $P_{\text{max},C1}$, which refers to the gain compression relative to the PA's small-signal gain. Since $G_{\text{PA}}(P_{\text{max},C1})$ is a normalized gain compression (≤ 0 dB), it is clear that

$$P_{\text{max,DPD\_in1}} < P_{\text{max},C1}. \tag{3}$$

Accordingly, the derived digital predistortion characteristics do not cover the entire power range of the input signal. This calls for an extrapolation of the PA's measured AM/AM and AM/PM characteristics so that the derived digital predistortion function covers the entire power range of the considered input signal. The use of an extrapolation technique for extending the DPD's operational power range is likely to introduce an error that will limit the linearity performance of the linearized amplifier. In addition, the insertion of the DPD shifts the average power of the signal, especially when highly nonlinear PAs are used. The average power variation at the input of the PA before and after the insertion of the DPD is given by the average power gain of the predistorter. This gain is a function of the input signal statistics and average power, and the amplifier's AM/AM characteristic.

As a first-order approximation, one can state that the DPD's average power gain is equal to the DPD's instantaneous gain at the average input power. Accordingly, this approach also leads to a variation of the PA's average input power between the characterization and linearization steps. This changes the behavior of the PA and, thus, further reduces the effectiveness of the linearization performance.

In the second approach, based on a constant peak power, the characterization is done in such a way as to avoid the need for extrapolation of the measured PA characteristics or, equivalently, the extracted digital predistortion function. For this purpose, the average power of the PA's input signal is increased during the characterization step in order to fully characterize the PA over its entire power range. This implies that the maximum power of the signal used in the characterization step ($P_{\max,C2}$) is equal to the input saturation power of the PA ($P_{\text{Sat,PA\_in}}$). Accordingly, the PA's average input power during the characterization step is

$$P_{\text{avg},C2} = P_{\text{Sat,PA\_in}} - \text{PAPR}_S. \tag{4}$$

Following such characterization, the maximum power at the input of the DPD is given by

$$P_{\text{max,DPD\_in2}} = P_{\text{Sat,PA\_in}} + G_{\text{PA}}(P_{\text{sat}}). \tag{5}$$

Thus, for the considered input signal, the maximum average power at the input of the DPD is

$$P_{\text{avg,DPD\_in2}} = P_{\text{Sat,PA\_in}} + G_{\text{PA}}(P_{\text{sat}}) - \text{PAPR}_s. \tag{6}$$

Accordingly, the average power level at the output of the DPD is

$$P_{\text{avg,DPD\_out2}} = P_{\text{avg,DPD\_in2}} + G_{\text{DPD}}(P_{\text{avg,DPD\_in2}}). \tag{7}$$

Hence, the average power variation at the input of the PA between the characterization and the linearization steps is

$$\begin{aligned}\Delta P_{\text{avg,PA}} &= P_{\text{avg,DPD\_out2}} - P_{\text{avg},C2}\\ &= G_{\text{PA}}(P_{\text{sat}}) + G_{\text{DPD}}(P_{\text{avg,DPD\_in2}}).\end{aligned} \tag{8}$$

Consequently, it is clear that a mismatch between the DPD and the PA nonlinearities will be observed due to the PA's significant average input power variation between the characterization and

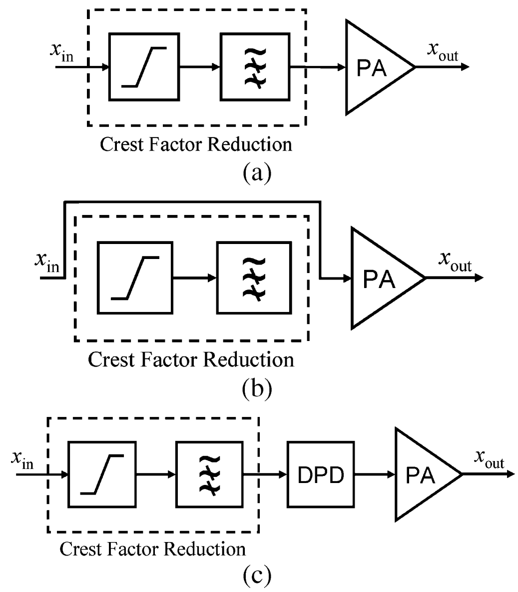

Fig. 4. Block diagram of the transmitter configuration for: (a) conventional PA characterization, (b) proposed PA characterization, and (c) PA linearization.

linearization steps. The effectiveness of the linearizer's performance depends on this average power variation. This is the main limitation of such a characterization/linearization approach.

IV. Synergetic Crest Factor Reduction and Digital Predistortion

It has been shown in Section IV that the two commonly used approaches for the synthesis of digital predistortion functions cannot be efficiently applied in the context of single iteration DPDs. This is mainly due to their inability to characterize the PA over the entire useful power range, while driving it with an average power level close to the average power level that will be applied during the linearization. This is largely due to the variation of the signal's PAPR before and after digital predistortion. Such characterization/linearization procedures call for an iterative process in order to converge to the best possible linearity results.

In order to overcome this problem, a new approach based on synergetic crest factor reduction and digital predistortion is proposed to improve the linearity performance in single iteration DPDs. This is based on the fact that the crest factor reduction diminishes the PAPR of the signal, while the predistortion function increases it. Accordingly, if the crest factor reduction and digital predistortion are turned on and off simultaneously, the average power and PAPR variations at the input of the PA in the characterization and linearization steps can be controlled and kept within a range that ensures a similar behavior of the PA at both steps.

In conventional approaches, the crest factor reduction is applied during the characterization step, as shown in Fig. 4(a). In the linearization step, as illustrated in Fig. 4(c), the DPD is added downstream of the crest factor reduction. This technique usually requires an iterative predistortion function synthesis process, as previously described. In the proposed approach, the crest factor reduction is turned off during the characterization

TABLE I
SIGNAL CHARACTERISTICS AT PA INPUT DURING CHARACTERIZATION AND LINEARIZATION STEPS

		CFR off at characterization	CFR on at characterization
Characterization step	P_{avg}	-16.1 dBm	-12.5 dBm
	PAPR	10.7 dB	7.1 dB
Linearization step	P_{avg}	-16.0 dBm	-16.6 dBm
	PAPR	10.5 dB	11.1 dB
P_{avg} Variation		0.1 dB	4.1 dB

process, as shown in Fig. 4(b). In the linearization step, both the crest factor reduction and digital predistortion functions are then applied simultaneously.

The proposed characterization/linearization procedure was tested on a high-power Doherty amplifier, and its performance was compared to that of the conventional approach. The device-under-test was driven by a single-carrier WCDMA signal.

The crest factor reduction block consisted of a limiter followed by a filter. The signal's PAPR before and after crest factor reduction was 10.7 and 7.1 dB, respectively. The signal characteristics at the input of the PA in both the characterization and linearization steps have been calculated for the two considered approaches. The results are presented in Table I, and one can clearly conclude that the proposed approach considerably limits the average power variation at the input of the PA between the linearization and characterization steps. In fact, this value was reduced from 4.2 dB, when the crest factor reduction was applied during the characterization step, to less than 0.1 dB, when the crest factor reduction was bypassed during the characterization step and applied only during the linearization step.

V. EXPERIMENTAL VALIDATION

The experimental validation was conducted on the device-under-test and experimental setup presented in Section II. First, the PA was characterized using the original WCMA signal, to which no crest factor reduction was applied $(\mathrm{PAPR} = 10.7\ \mathrm{dB})$. The measured AM/AM and AM/PM characteristics were then used to synthesize a conventional memoryless lookup table (LUT) based DPD. In the linearization step, the crest factor reduction algorithm was turned on, and several clipping thresholds were applied. The crest factor reduction algorithm used in this study is similar to that proposed in [3]. The resulting signals were then used to drive the DPD. For each signal, the average power level at the input of the DPD was set to the maximum possible value that will boost the output power without saturating the DPD and PA. The clipping and filtering based crest factor reduction technique generates in-band distortion that increases the error vector magnitude (EVM). This sets an upper limit on the clipping factor that can be used while satisfying the standards requirements for the EVM. Typically, for WCDMA signal, a PAPR reduction by 3–4 dB, results in an EVM of 8%, which is still compliant with the standard requirements value of 17% [3]. In the proposed technique, the clipping factor is in the range of the PA's gain compression at saturation (typically 3–4 dB). Accordingly, the proposed synergetic crest factor reduction and DPD technique can be applied while maintaining a standard compliant EVM level.

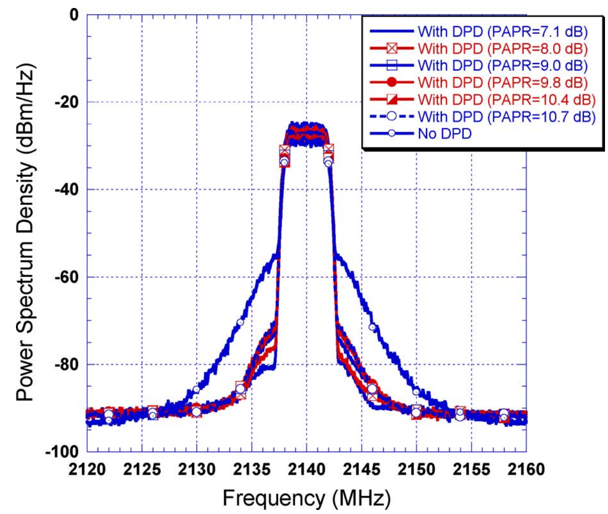

Fig. 5. Measured spectra at the output of the linearized PA.

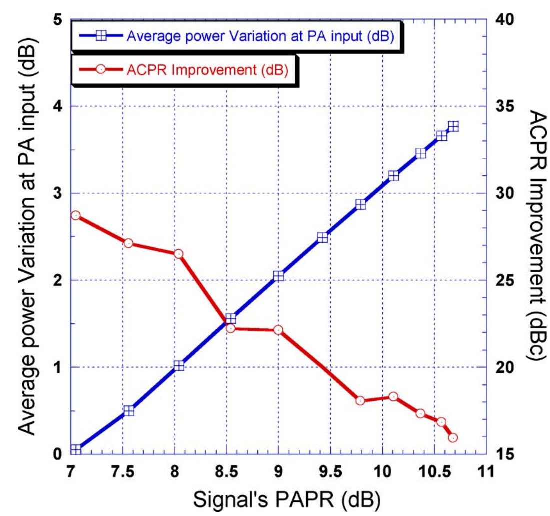

Fig. 6. Measured ACPR improvement at the output of the linearized PA, and average power variation at the PA input.

The measured spectra at the output of the linearized PA are presented in Fig. 5. Each of these curves was measured for an output average power backoff from the saturation equal to the PAPR of the considered signal. This figure shows that, as the peak-to-average ratio of the driving signal decreased, the output power, as well as the linearity performance of the linearized PA increased simultaneously. In fact, the highest output power level and the best linearity performance were obtained for the signal with the lowest PAPR value. However, when the signal used for the PA characterization $(\mathrm{PAPR} = 10.7\ \mathrm{dB})$ was applied at the input of the DPD in the linearization step, the observed linearity improvement was the lowest.

Fig. 6 reports the adjacent channel power ratio (ACPR) improvement after linearization measured at 5 MHz as a function of the PAPR of the driving signal. In this figure, the signal's PAPR refers to the PAPR of the signal used to drive the predistorter. The characterization step was performed with the non-clipped original signal. The average power variation at the input of the PA between the linearization and characterization steps is also plotted in Fig. 6. According to these results, the use of the same signal in both the characterization and linearization steps $(\mathrm{PAPR} = 10.7\ \mathrm{dB})$ led to an ACPR improvement of 16 dBc and introduced 3.8-dB variation in the PA's average input power. As the crest factor of the signal used to drive the DPD was reduced, the ACPR improvement increased, and the average power variation at the input of the PA decreased. These reach 29 dBc and 0.1 dB, respectively, for a signal with a 7.1-dB PAPR.

These results clearly illustrate the effectiveness of the proposed approach in improving the linearity performance in single iteration DPDs.

VI. Conclusion

In this paper, the sensitivity of high PAs to the driving signals' characteristics was evaluated experimentally. It was shown that the PA's nonlinear behavior, especially its AM/AM characteristics, varied considerably, with respect to the input signal's average power. On the other hand, the statistics of the signal almost did not affect the amplifier's behavior. Following this PA behavior's dependency on the average power, it has been shown that state-of-the-art PA characterization and digital predistortion synthesis approaches cannot be efficiently used in single iteration DPDs. A novel approach based on the synergetic use of crest factor reduction and digital predistortion was then proposed to solve this problem. In the proposed approach, the crest factor reduction block is bypassed during the characterization step and turned on simultaneously with the DPD in the linearization step. The performance of this approach was assessed experimentally. Measurement results showed an ACPR improvement at the output of the linearized PA of 16 and 29 dBc, respectively, when the conventional and proposed approaches were used.

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