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Abstract— **Radio frequency power amplifiers (PAs) play a key-role in transceivers for mobile communications and their linearity is a crucial aspect. In order to meet the linearity requirements dictated by the standard at a reasonable efficiency, the usage of a linearization technique is required. In this paper we propose a linearization by means of a new type of digital predistorter, defined directly in the I-Q domain. The architecture of the proposed predistorter can be understood as an enhancement of the memory polynomial model (MPM) by means of additional I-Q terms. The usage of the proposed predistorter allows a more robust linearization of the whole RF transmitter because the enhancement of the model with additional I-Q terms can guarantee a more versatile compensation which is beneficial when the distortion comes from the joint contribution of the PA and the quadrature modulator. The proof of concept is achieved by measurements on a commercial PA in GaN technology and the performance of the proposed predistorter is illustrated.**

Index Terms—**power amplifier, gallium nitride (GaN), memory effects, linearization, memory polynomial, digital predistortion.**

I. INTRODUCTION

MICROWAVE power amplifiers can achieve a higher efficiency in terms of transmitted power vs. supplied power if driven as close as possible to the saturation point. Unfortunately the more the power amplifier (PA) approaches saturation, the more it behaves nonlinearly and it does not fulfill the linearity requirements dictated by the mobile communication standard. Therefore a linearity-efficiency trade-off arises which RF engineers have to deal with if they want to have the PA working at a reasonable efficiency.

Back-off strategies can be used to avoid nonlinear effects in power amplifiers: the dynamic range of the amplifier input signal is shifted down to a lower power level so that the amplifier output is not severely affected by nonlinear behavior. The solution to avoid a too drastic back-off is the recourse to a linearization technique. Different linearization methods exist able to reduce the nonlinear distortions while keeping the PA as efficient as possible [1]. Linearization by digital pre-distortion is a method in which digital signal processing techniques are applied to the baseband signal to compensate the nonlinear distortions by means of a digital system called a predistorter. Common approaches deal with Volterra, Hammerstein and Wiener models [2],[3]. In order to lower the computational complexity of such models the memory polynomial (MP) model was introduced in [4] and widely used since then because of its reduced computational cost [5],[6]. Nevertheless, when using digital predistortion, one of the difficulties is to define an adaptive and robust predistorter architecture not only able to cope with the nonlinearities and memory effects of the PA, but accounting also for distortion contributions arising from other sources, like the quadrature modulator (QM). The compensation of distortion caused by the QM is a well-known issue in the state-of-the-art and it has been showed that a Volterra model defined in the I-Q components is suitable for this task [7]. A solution for a joint compensation of PA and QM was introduced in [8],[9] with different approaches.

In this paper the proposed predistorter represents an alternative solution to achieve a robust PA compensation able to cope also with I-Q impairments from the QM. This advantage can be achieved because the presented predistorter is enhanced in the I-Q domain and its versatile architecture can also handle PM/AM and PM/PM distortion contributions besides the common AM/AM and AM/PM generated by the RF PA. In the following sections we explain the derivation of the enhanced I-Q memory polynomial (EIQMP) and how it can be used as a predistorter. Then EIQMP and MP predistorters are compared by means of measurements on a GaN PA and finally the conclusions are outlined.

II. ENHANCED I-Q MEMORY POLYNOMIAL MODEL

In this section we describe the model architectures considered in this work and whose performance has been compared by means of measurements on commercial amplifiers.

A. Memory Polynomial Model

The memory polynomial model (MPM) is an equivalent baseband model which has been widely used in literature for both PA modeling and PA predistortion [2]-[6]. In its conventional form [4], it can be formulated as:

$$y(n) = \sum_{p=1}^{P} \sum_{m=0}^{M} c_{p,m} x(n-m) |x(n-m)|^{p-1} \qquad (1)$$

where $x(n) = x_I(n) + jx_Q(n)$ and $y(n) = y_I(n) + jy_Q(n)$ are the complex baseband envelopes of the RF signals $x_{RF}(t)$ and $y_{RF}(t)$ that represent respectively the RF input and output of the PA, $c_{p,m}$ are the MPM complex coefficients, P is the maximum nonlinearity order and M is the memory depth of the model.

B. I-Q Memory Polynomial Model

If we assume in (1) that M=0, P=3 and $c_{p,m}$=1 for every p, then we obtain the following expression:

$$y_I(n) = x_I(n) + x_I(n)|x(n)| + x_I(n)x_Q{}^2(n) + x_I{}^3(n) \qquad (2)$$

$$y_Q(n) = x_Q(n) + x_Q(n)|x(n)| + x_I{}^2(n)x_Q(n) + x_Q{}^3(n) \qquad (3)$$

From (3)-(4) it is shown that in the MPM we have actually $y_I = f_1(x_I, x_Q)$ and $y_Q = f_2(x_I, x_Q)$, where the functions $f_1(x_I, x_Q)$ and $f_2(x_I, x_Q)$ have a polynomial expression, apart for the terms $|x(n)|^{p-1} = \sqrt{(x_I{}^2(n) + x_Q{}^2(n))^{p-1}}$, p even. This observation inspires the idea of expanding the model (1) inserting additional monomials of the input I-Q components. If we also keep the dynamic properties of (1), then we obtain a new model that can be described as follows:

$$y_I(n) = \sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M} a_{p,k,m} x_I{}^{p-k}(n-m) x_Q{}^k(n-m) \qquad (4)$$

$$y_Q(n) = \sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M} b_{p,k,m} x_I{}^{p-k}(n-m) x_Q{}^k(n-m) \qquad (5)$$

We here refer to the new topology in (4)-(5) as the I-Q memory polynomial model (IQMPM). The model (4)-(5) can be expressed in a more compact form introducing the set of complex coefficients $d_{p,k,m} = a_{p,k,m} + jb_{p,k,m}$:

$$\begin{aligned} y(n) &= y_I(n) + jy_Q(n) \\ &= \sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M} d_{p,k,m} x_I{}^{p-k}(n-m) x_Q{}^k(n-m) \end{aligned} \qquad (6)$$

The usage of a model defined directly in the I-Q components has been shown to be beneficial to model and compensate I-Q impairments generated in the quadrature modulator [7],[9]. The idea of this paper is to use such a representation to be able to predistort both QM and PA at the same time.

C. Enhanced I-Q Memory Polynomial Model

In order to achieve an improved compensation a further innovative step is represented by the inclusion in (6) of all the terms depending from the samples absolute values$|x(n-m)|$. In such a way we obtain the enhanced I-Q memory polynomial model (EIQMPM):

$$y(n) = \sum_{\substack{p=2 \\ p\,even}}^{P}\sum_{m=0}^{M} f_{p,m} x(n-m)|x(n-m)|^{p-1} + \qquad (7)$$

$$+ \sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M} g_{p,k,m} x_I{}^{p-k}(n-m) x_Q{}^k(n-m)$$

where $f_{p,m}$ and $g_{p,k,m}$ are the EIQMPM complex coefficients, P is the maximum nonlinearity order and M is the memory depth of the model. The enhancement of MPM to obtain EIQMPM leads to a more adaptable structure, able to model and predistort PM/AM and PM/PM distortion effects that are caused by I-Q impairments in the QM, keeping at the same time the satisfying performance of MPM when only distortion from PA is produced.

III. DIGITAL PREDISTORTION USING EIQMPM

The model architectures presented in the previous section can be applied as behavioral models for RF PAs and their performance compared. One of the most used figures of merit for the evaluation of PA behavioral models is the normalized mean squared error (NMSE). It can be expressed in dB as follows:

$$NMSE = 10\log_{10}\left(\frac{\sum_{n=1}^{N}|\hat{y}(n) - y(n)|^2}{\sum_{n=1}^{N}|y(n)|^2}\right) \qquad (8)$$

where $\hat{y}(n)$ is the model output sequence, $y(n)$ is the sequence of I and Q samples measured from the PA output and N is the number of acquired samples. The NMSE evaluation of the presented architectures when used as PA models is a very useful information from the perspective of digital predistortion, because very often the assumption is that if a model proves to be accurate as an equivalent baseband model of an RF PA, then the same structure can perform well as a digital predistorter also.

So once we have a good PA model, the next step is to invert it to obtain a predistorter with a similar structure. This inversion operation has a solid theoretical foundation for a particular class of nonlinear models, i.e. Volterra-like models [10]. Moreover from the theory of the pth order inverse of nonlinear systems we know that, in the assumption of a Volterra-like nonlinear dynamic system, the post-inverse of the system is identical to the pre-inverse of the system [10]. These theoretical results apply to all our models because, similarly to the MPM, the IQMPM and EIQMPM can be understood as derivations of a Volterra model defined in the I-Q components, like the one used in [7]. Hence, for all the considered structures, the predistorter identification can be performed directly without the inversion of any PA model.

Assuming the EIQMP architecture defined in (7), the EIQMP post-distorter is formulated as follows:

$$\begin{aligned} x(n) &= \sum_{\substack{p=2 \\ p\,even}}^{P}\sum_{m=0}^{M} f_{p,m} z(n-m)|z(n-m)|^{p-1} \\ &+ \sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M} g_{p,k,m} z_I{}^{p-k}(n-m) z_Q{}^k(n-m) \end{aligned} \qquad (9)$$

$$z(n) = z_I(n) + jz_Q(n) = \frac{y(n)}{G} \qquad (10)$$

where G is the voltage gain of the PA and z is the complex envelope of the PA output normalized to the voltage gain.

Making use of the theoretical results in [10], we can directly identify the post-distorter and then use the same coefficients to define the predistorter (Fig. 1).
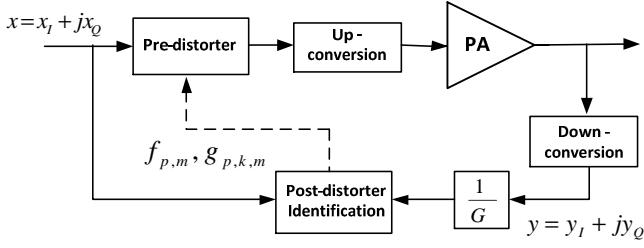
Fig. 1. Block diagram explaining the principle of the used predistortion algorithm. In the assumption of a Volterra-like model of the PA, its post-inverse is identified and then used as a predistorter (pre-inverse).

This identification procedure is commonly used in PA predistortion [5], [6] and it is usually addressed as the indirect learning paradigm. Using the PA input and output I and Q samples, the post-distorter parameter extraction can be performed using the least squares (LS) algorithm [2]-[6]:

$$h = (M^H M)^{-1} M^H x \qquad (11)$$

where $h=[f\ g]$ is the vector of coefficients and M is the model matrix built according to (7). In this work the parameter extraction was performed using the Moore-Penrose pseudo-inverse of M because this technique provides a more robust solution to the system (11) and avoids instability in parameter extraction due to the eventual high condition number of the model matrix M.

IV. MEASURED RESULTS

The predistortion algorithms described in the previous sections were applied to a GaN PA from Cree with a nominal gain of 16.8 dB and a saturated power of 35 dBm at 2 GHz. The measurement set-up in Fig. 2 shows that the device under test (DUT) includes the input and output bias tees. This GaN PA already showed relevant memory effects when characterized using a similar set-up [11]. The measurements were performed using an average input power of 9 dBm from the signal generator R&S SMBV100A, so that the PA was operating at a gain compression of 3 dB at the peak of the input envelope. The RF carrier was set to 2 GHz and the amplifier was biased with a drain bias V_{DD} of 28V and a quiescent drain current I_D of 100 mA. The input signal used for the measurements was a WCDMA signal, compliant with the 3GPP standard and having a bandwidth of 3.84 MHz, a PAPR of 3.44 dB and using QPSK modulation. I and Q waveforms were acquired from the PA input and output ports using a sample rate of 80 MHz at the signal analyzer. The acquired samples were then time-aligned using cross-correlation and used for the predistorter identification. Once the predistorter is identified, the predistorted signal is created and uploaded to the signal generator to be applied to the PA. The predistortion performance was evaluated in two different cases:

Case A) *PA distortion*: GaN PA excited with a 3GPP WCDMA signal of 9dBm average input power.

Case B) *PA distortion and I/Q impairments*: GaN PA excited with a 3GPP WCDMA signal of 9dBm average input power and with I offset of 5%, Q offset of 5% and I/Q quadrature offset of 10 degrees.
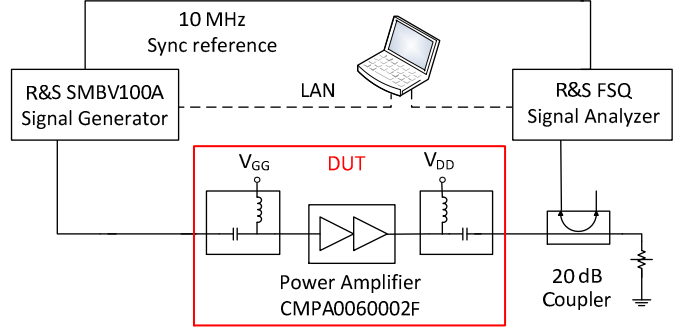

Fig. 2. Measurement set-up used in this work. For PA biasing two external bias tees HP-11590B were used both at the input and output ports of the PA.

A. Measurements on PA predistortion

The predistortion results in Fig. 3 show the measured spectra of the PA input and output signal compared with the measurements obtained when applying an MP predistorter (MPPD), an I-Q MP predistorter (IQMPPD) and an Enhanced IQMPPD (EIQMPPD) before the PA. In all of the cases a set of 20,000 IQ samples was used to extract the parameters according to (11). ACLR (adjacent channel leakage ratio) measured values are listed in Tab.1 for all the cases. The results shown in Tab.1 and Fig.3-4 refer to MP, IQMP and EIQMP predistorters defined with a sample rate f_m of 40 MHz, a maximum nonlinearity order P=3 and a memory depth M=3. The chosen values for P and M are based on an NMSE study. The calculated NMSE when applying the same structures as PA models is also listed in Tab.1. It is shown that the EIQMPPD and MPPD achieve similar performance and both manage to linearize the PA so that it has a good margin of about 15 dB compared to the ACLR of 33dB specified for WCDMA handsets by the 3GPP standard [12]. The IQMPPD performs worse due to the lack of the terms included in the EIQMPPD.
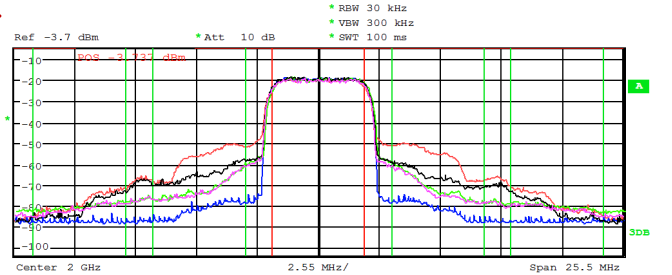

Fig. 3. Comparison of the measured spectra when applying a 3GPP UMTS signal. The different traces refer to PA input (blue), PA output (red), PA output after MPPD (green), PA output after I-Q MPPD (black) and PA output predistorted using EIQMPPD (magenta). Measured values of the upper and lower ACLR are listed in Tab.1 for all the traces.

TABLE I
MEASURED PREDISTORTION PERFORMANCE

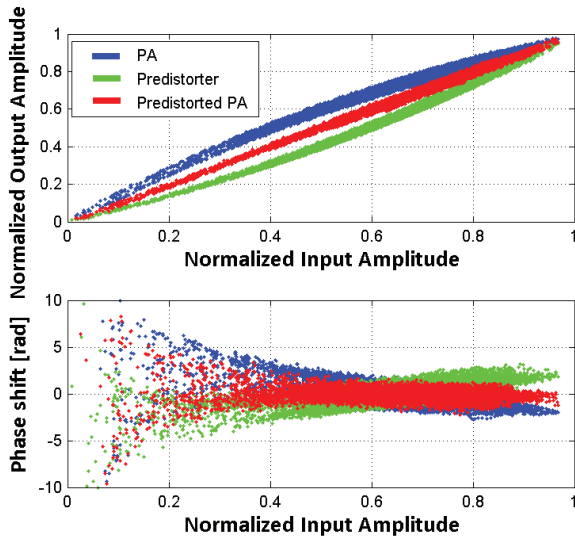| Measurement	NMSE [dB]	EVM [%]	Adjacent Channel [dB] Lower-Upper	Alternate Channel [dB] Lower-Upper
PA Input	-	0.4	-61.0/-60.8	-67.8/-67.8
PA Output	-	2.9	-34.8/-33.8	-56.6/-56.2
MPPD + PA	-38.94	1.1	-49.4/-48.8	-61.3/-61.3
IQMPPD + PA	-36.45	1.2	-44.3/-44.8	-59.0/-60.2
EIQMPPD+PA	-39.20	1.1	-48.4/-48.0	-60.8/-60.6

Fig. 4. Measured input vs. output amplitude (AM/AM) and input amplitude vs. phase shift (AM/PM) curves of PA (blue), ENIQMP predistorter (green) and predistorted PA (red) using an EIQMPPD with f_m = 40 MHz, M = 3, P =3.

B. Measurements on PA predistortion with I/Q impairments

In this operational case, the same WCDMA signal was applied to the PA with the described additional I/Q impairments from the dedicated panel of the signal generator, in order to evaluate the predistortion performance in a scenario where the distortion in the RF transmitter is caused by the joint contribution of the PA and the quadrature modulator. From Fig.5 and Tab.2 we can see that in this scenario the EIQMPPD totally outperforms the MPPD whose architecture is not able to cancel the PA distortion in presence of I-Q impairments. The results in Fig.5 and Tab.2 refer again to predistorters defined with f_m =40MHz, P=3 and M=3. The predistorter identification was performed as in the Case A).

V. CONCLUSION

This paper proposes an enhanced I-Q memory polynomial predistorter (EIQMPPD), whose novelty consists in enhancing the MPPD by means of additional I-Q nonlinear terms. A comparison of the linearization performance was carried out measuring a commercial GaN PA excited with a WCDMA signal. Measured results show that the EIQMPPD can achieve a more robust linearization than MPPD. In a scenario of joint distortion form PA and quadrature modulator, the EIQMPPD allows a compensation which is not possible with MPPD, because the additional I-Q terms give the capability to compensate PM/AM and PM/PM distortion effects. The higher versatility of the proposed architecture is achieved by means of a higher number of parameters, but such an increase in the computational cost is not a problem for the most common implementations in digital hardware.
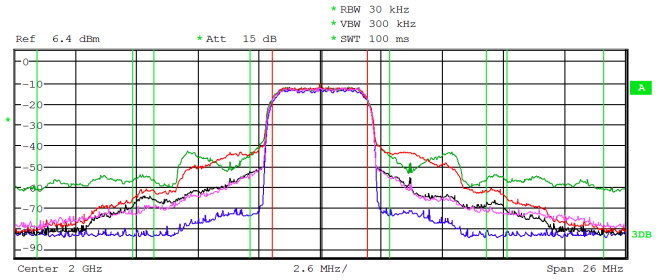
ACKNOWLEDGMENTS

Fig. 5. Comparison of the measured spectra when applying a 3GPP UMTS signal with I-Q impairments (I offset of 5%, Q offset of 5% and quadrature offset of 10 degrees). The different traces refer to PA input (blue), PA output (red), PA output after MPPD (green), PA output after I-Q MPPD (black) and PA output predistorted using EIQMPPD (magenta). Measured values of the upper and lower ACLR are listed in Tab.2 for all the traces.

TABLE II
MEASURED PREDISTORTION PERFORMANCE WITH I/Q IMPAIRMENTS

Measurement	NMSE [dB]	EVM [%]	Adjacent Channel [dB] Lower-Upper	Alternate Channel [dB] Lower-Upper
PA Input	-	8.6	-61.1/-60.9	-68.2/-68.2
PA Output	-	7.6	-34.8/-34.1	-58.1/-57.8
MPPD + PA	-17.90	8.4	-34.5/-34.5	-44.2/-44.2
IQMPPD + PA	-33.59	1.3	-46.2/-47.5	-61.3/-62.7
EIQMPPD+PA	-34.22	1.3	-47.2/-48.5	-60.7/-60.4

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