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An Overview of RF Power Amplifier Digital Predistortion Techniques for Wireless Communication Systems

This paper presents an overview of different Digital Predistortion (DPD) techniques used in microwave Power Amplifier (PA) linearization. Different DPD approaches are considered with both static and dynamic (memory effects) behavioral models. The most suitable solutions for facing the new challenges to linearize high-bandwidth amplifiers are discussed, which is demanded by most of the new telecommunications standards and emergent technologies.

Keywords: Power Amplifiers, Linearization, Digital Predistortion.

Power amplifiers (PAs) are one of the most essential components in communication systems and are inherently nonlinear [1–4]. Non linearity in power amplifiers causes spectral re-growth beyond the signal bandwidth, which interferes with adjacent channels. It also causes distortions within the signal bandwidth, causing increase in bit error rate at the receiver. According to traditional concepts, PA efficiency and linearity are mutually exclusive specifications in power amplifier design [5], whereas in present scenario digital predistortion techniques allow PA to work in extended linear region and compensate time varying amplitude and phase distortions as well as memory effects in PAs [6]. Linearization can be considered as the process of cancellation of distortion components, especially cancellation of third-order Intermodulation (IM3) distortion, and the performance of the linearization method is measured by the amount of the distortions cancelled. IM3 components generated by PAs depend on many input environments such as amplitude, signal bandwidth, self-heating, aging, etc [7–10]. In modern communication systems digital predistortion techniques are used to linearize the PAs, thus reduce Error Vector Magnitude (EVM), Adjacent Channel Power Ratio (ACPR) and improve Power Added Efficiency (PAE) [11–14]. Linearity is achieved with the help of various predistortion techniques by linearizing either the gain or the phase, or by linearizing both gain and phase responses of the system. Predistortion techniques can be broadly classified as feed-forward, feedback and digital predistortion techniques [4, 6]. Different linearization techniques have different sensitivities to memory effects [15]. Feedback and feed-forward systems measure the actual output distortion, including the memory effects, and therefore are considered less vulnerable to memory effects [13, 14, 16].

Memory effects may cause severe degradation in the performance of the linearizer with predictive systems like predistortion and Envelope Elimination and Restoration (EER), because they are vulnerable to any changes in the behavior of the amplifier [3, 17]. However, if the behavior of spectral components is deterministic, then there is no fundamental reason to consider predictive linearization techniques poorer than closed loop systems like feedback or feed-forward. Envelope feedback based techniques are inefficient to correct AM-PM distortion therefore they are generally restricted to relatively linear class-A or AB amplifiers. Polar-loop techniques overcome the inability of envelope feedback to correct AM-PM distortion [29], but the major disadvantage of this technique is that they require different bandwidths for amplitude and phase feedback paths, resulting in different levels of improvement of AM-AM and AM-PM characteristics. Cartesian feedback technique applies modulation feedback in *I* and *Q* components [30], to solve the problems related to wide band signals. In [4], improvement in the ACPR by 35 dB with efficiency of 60% has been reported, which shows Cartesian feedback technique is efficient even in highly nonlinear class C PAs. Feed-forward techniques are considered the most suitable for linearizing systems based on very wide band multicarrier applications. Normally feed-forward technique gives improvements in distortion ranging from 20 to 40 dB, but to achieve this, amplifiers are driven well into the back-off to improve linearity. Therefore the overall average efficiency of this technique is considered 10 to 15% for typical multicarrier signals [4]. Digital predistortion techniques provide several advantages over other predistortion techniques, because it does not have a loop nor delay issues; it is operated before the amplifier, which means the signal processing does not consume large power. Above all the signal processing can be achieved in a Digital Signal Process (DSP), making it much simpler in physical layout. This paper reviews different Digital Predistortion techniques (DPD) and provide an insight for the designers to understand the major prerequisites of a linear system and guide a suitable solution for designing a DPD technique for linearization, taking into account various parameters affecting the performance of the DPD based system.

The paper is organized as following: in Sect. II the major non linearity issues in a PA and their relative models are described. In Sect. III the models adopted to represent PAs behavior are described. Then in Sect. IV the DPD techniques adopted to linearize nonlinear PAs are described and compared, and finally some conclusions are drawn.

Distortion analysis. Linearization techniques are used in PAs to improve linearity and to allow the operation of PA with less back-off to increase the overall efficiency of the system. In order to maximize efficiency and minimize the distortion in any system, proper understanding of the working, along with the behavior of distortion introduced by PA is necessary. Nonlinearity limits the operative region of a PA and restricts the system to work with lower efficiency. An accurate modeling of PA allows the designer to overcome the issues related to nonlinearities. PA models can be classified according to the type of data needed for their extraction [18, 20]. Several modeling considerations are available in literatures [3, 4, 14, 16, 19, 20, 21]. In broad, nonlinear models of PA are classified as:

i) Memoryless models
ii) Models with memory
iii) Bandpass models
iv) Baseband models
v) Block Input / Output models
vi) Analytical models
vii) Non-linear differential equation models

In the above classifications, PA models can be defined mutually exclusive as well as mutually dependent also. In the passband, a strictly memoryless PA can be described as a nonlinear function that maps a real valued input to a real valued output. Over a closed interval for input signal $x(t)$ the memoryless nonlinearity can be approximated by a power series represented by a polynomial function as

$$y(t)=\sum_{n=1}^{N} a_n \cdot x^n(t), \tag{1}$$

where a_n – are real valued coefficients, $x(t)$ is the passband PA input, and $y(t)$ is the passband PA output. In baseband, equation (1), turns out to be

$$y(t)=\sum_{\substack{n=1\\ n\ \text{odd}}}^{N} a_n \cdot x(t)\cdot\left|x(t)\right|^{n-1}. \tag{2}$$

In this case, $x(t)$ is the baseband PA input, and $y(t)$ is the baseband PA output. In equation (1) and (2), a_n are real values. A PA is strictly memoryless, if it will only introduce amplitude distortion in the system, which is also known as AM-AM distortion. AM-AM distortion results in the compression or expansion of the output signal amplitude near the saturation or cut-off region of the active device respectively. Performance of any predistortion function primarily depends on the accuracy of the PA model. Power series polynomial modeling is considered a straight forward and an easy way to calculate spectral components in nonlinear systems. A general approach to model the nonlinearity in power series is to model the output of the system with a third or higher order polynomial. Expanding equation (1), results in [4, 15]:

$$y=a_1\cdot x+a_2\cdot x^2+a_3\cdot x^3\dots. \tag{3}$$

Where, the linear small signal gain is represented by a_1. Similarly a_2 and a_3 are the gain constants of quadratic (square law) and cubic nonlinearities. Up to the third order, the output comprises the fundamental signal (ω_1), the second harmonic ($2\omega_1$) and dc generated by a_2x_2 and the third harmonic ($3\omega_1$) generated by a_3x_3. If the coefficient a_n is complex in nature then it is often referred to as quasi memoryless power amplifier. Models such as Volterra series, Artificial Neural Network, Saleh model, Blum and Jeruchim models are widely used to model a PA with memory effects [4, 14, 16, 18]. In passband a nonlinear PA with memory can be approximated by Volterra series, as

$$y(t)=\sum_{k}\int\dots\int h_k(\tau_k)\prod_{i=1}^{k} z(t-\tau_i)\,d\tau_k\ . \tag{4}$$

Where, $\tau_k=[\tau_1,\dots,\tau_k]$, $h_k(\cdot)$ is the real value of the k-th order of Volterra kernel, and $d\tau_k = d\tau_1 d\tau_2, \dots, d\tau_k$. As reported in [21] kernel, the baseband version of equation (4) has the same form as (2) except that, the coefficients a_n are complex values. Memory effects can basically be defined as the changes in the behavior of transfer function of a PA with respect to change in time or input signal frequency. Causes behind the memory effects can broadly be classified as electrical memory effects and thermal memory effects [10].

The former is generated due to frequency dependent envelope and node impedances of PA, whereas the latter is caused due to variation in temperature and component impedances resulting from electro-thermal coupling.

Power amplifier models. In the frequency domain, nonlinearity in PA generates new spectral components. A system is considered nonlinear and memoryless only if the nonlinearity coefficients in equation (3) have real values over the complete frequency range of working [4, 6]. Whereas a system with complex valued coefficients represents phase shift between the input and output signals, thus representing a nonlinear system with quasi-memoryless behavior [4]. It is extremely difficult to implement a single function based model for any communication system, especially when PA behaves differently at different power regions with both gain expansion and compression along with consistent amplitude and phase changes in different power regions. A possible solution for such cases is proposed in [2], where a piecewise curve fitting model is used, in which the nonlinear curves are divided into several segments based on input power levels and then each segment is linearised using different functions. Often, it is assumed that even order distortions in the PA does not generate distortion around the carrier frequency and thus causes no effect on the baseband models. However, Ding [3] suggests that the polynomial order can be reduced by including the even order terms also. Power series polynomial functions are not feasible to be used with highly nonlinear regions of PA, as it can be observed from Fig. 1, where the order of the power series significantly changes near the cutoff and saturation region of the active device [22], which further gives rise to computational complexity to calculate coefficients of the function.

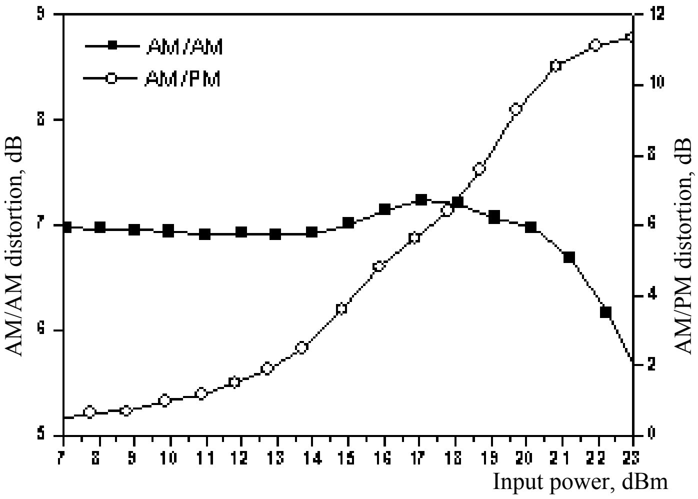

Fig. 1. Normalized AM/AM and AM/PM Behavior of a PA

Several PA models were introduced to overcome these issues. The Saleh model [18], which was initially designed for traveling wave tube (TWT) amplifier, is recommended as the standard PA model by IEEE broadband wireless access group [19]. Saleh model is optimized for TWT amplifiers and is not well suited for modeling solid-state power amplifiers (SSPA) [20]. Rapp model [7] is a PA model well suited for SSPA, but model is showing linear behavior at the low input amplitudes also. Ghorbani model [7] allows modeling gain and phase function of SSPA to compensate nonlinearities at low amplitude, and it is considered suitable to model FET amplifiers. The Hammerstein model represents a linearly filtered version of the response of a static nonlinearity and Weiner model in contrast distorts a pre-filtered version of the input signal.

Digital predistortion techniques. DPD techniques are considered more efficient than analog predistorters, because they are applied before the power amplifier where insertion loss is less critical and also due to their ability to reduce Intermodulation Distortion (IMD) significantly [4, 6, 15]. Due to limited DSP computational rates, they are limited to low bandwidths applications, but with the advent of higher processing abilities in DSP it is now possible to predistort wideband systems also [12, 13]. DPD techniques utilize the immense processing abilities of DSP devices, and exploit them to structure and implement the required predistortion characteristics. DSP based predistorters can work with analog-baseband, digital-baseband, analog-IF, digital-IF, or analog-RF input signals [7]. Digital predistortion techniques can be classified broadly as Static predistortion and Adaptation based predistortion techniques. Complex vector mapping look up table (LUT), Complex Gain LUT and Cartesian feedback techniques falls under the class of static predistortion technique, whereas Secant Method and Linear Convergence Methods are associated with adaptation based predistortion technique [REF]. To compensate AM/AM and AM/PM distortion, complex vector mapping LUT technique adds an error vector to the input signal, whereas in complex gain LUT technique the input signal is multiplied by a complex gain vector which is optimized and stored in the LUT. The envelope of the input signal determines the size of index in the LUT. Cartesian feedback technique does not require LUT, but is considered less stable than other techniques in static predistortion techniques [23]. Architecture of a LUT based digital adaptive predistortion system is shown in the Fig. 2.

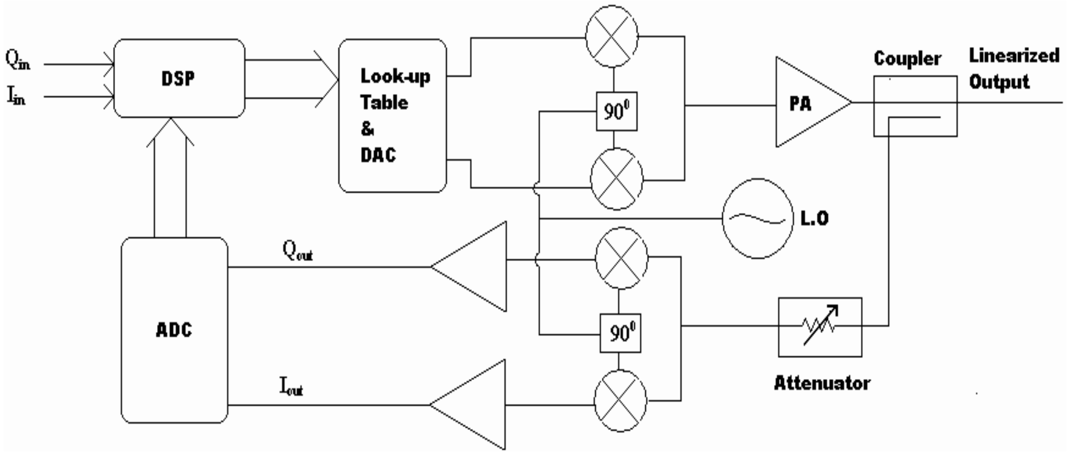

Fig. 2. Digital Adaptive Predistortion System

Adaptation based predistortion methods requires a continuous computation to estimate the gradient of the output power. The DPD takes the difference between the input and the scaled output signal and the adjacent channel interference power is minimized when the error between the two is completely suppressed. The gradient of output power is continually updated to linearize the system. Generally DSPs are used to implement adaptation, but analog adaptive algorithms have also been reported [17]. Baseband predistorters mainly use LUTs based on comparison of instantaneous envelope values [7, 8, 16], which is also used in RF-predistortion technique [24]. The secant method and linear iteration methods are the common methods for LUT adaptation using time-domain comparison. Common methods for determining the required update are: comparison of the time-domain input and output signals [7, 8], adjacent channel power measurements [9] and temperature measurements [10]. Linear iteration can be derived by the method of successive substitutions [8] as

$$LUT_{n+1}(V_{in}(n)) = LUT_n(V_{in}(n))\left\{1+\alpha\frac{(V_{out}(n)-V_{in}(n))}{V_{out}(n)}\right\}. \tag{5}$$

Polar and RF-predistortion systems omit the division by $V_{out}(n)$ causing slower convergence and mapping predistorters [7] also uses the same form. The updated algorithm can be written as

$$LUT_{n+1}(V_{in}(n)) = LUT_n(V_{in}(n)) - \alpha(V_{out}(n)-V_{in}(n)). \tag{6}$$

In equations (6) and (7), n is the index of the current iteration, LUT (V_{in}) is the value of LUT entry corresponding to the input amplitude value $V_{in}(n)$, $\Delta V(n) = V_{out}(n) - V_{in}(n)$, $V_{out}(n)$ is the PA output envelope and α is a constant that determines the convergence speed of the iteration. The adaptive formulae can be applied to both phase and amplitude LUTs. At the cost of complex hardware, secant method [25] offers faster convergence, it also requires information about previous LUT and signal values to achieve optimum performance. Table 1 shows a review of some of the research outcomes published.

Table 1

Review of Published Predistortion Schemes

Predistortion Type	RF/BB	Reported In	Memoryless/ Memorybased	ACP Improved, dB
Phase/Amplitude	RF	[15]	Memoryless	25
Mapping	BB	[6]	Memoryless	≈20
Polar	BB	[10]	Memoryless	≈20
Phase/Amplitude	RF	[16]	Memoryless	≈20
Phase/Amplitude	RF	[9]	Memoryless	≈8
Memory Polynomial	BB	[17]	With Memory	16
Digital	RF	[18]	Memoryless	≈15
Mapping	BB	[19]	Memoryless	≈30

DPD techniques reported in [2], shows a great reduction in Normalized Root Mean Square Error (NMSRE) and Adjacent Channel Power Ratio (ACPR), when memory based DPD techniques are used. Table 2 shows comparison between the different approaches to linearize PAs developed with two different technologies. For PAs designed using LDMOS technology, the AM/AM distortion mainly arose in low-power levels. It is evident from the Table 2, that NRMSE performance degrades very badly, up to 44.9% in

LDMOS PA, because large gain reduction and rise in memory effects take place in the PA when the input signal magnitude is low, whereas with increase in the input power the output of the PA linearises, but phase changes dramatically over the overall power range. Similarly, in case of GaN PA, the memoryless DPD can compensate static nonlinearities, but memory effects still remain in the system. Table 2 shows, in case of GaN PA, the performance of memory DPD provides outstanding performance by reducing the first adjacent channel by over 30 dB from –27 to –57 dBc and NRMSE reduced from 44.9 to 2.10%. It is apparent from the study made above that in any case it is always advantageous in linearizing the PAs by using DPD techniques and the use of memorybased DPD technique provide and edge over memoryless DPD for PAs in applications like transmitters in base stations.

From the study it is very clear that choice of DPD technique depends on several factors such as, type of PA and its bandwidth of operation, the algorithms used in DPD, availability and cost of high speed DSP, size of LUT required, and other factors affecting the PA like, time, temperature and similar parameters causing memory effects.

Table 2

NRMSE and ACPR Performance of GaN and LDMOS PAs

		NRMSE, %	ACPR, dBc	
			±5 MHz	±10 MHz
GaN PA	Without DPD	16.7	–34.6/–34.1	–48.3/–48.1
	Memoryless DPD	4.58	–53.7/–49.6	–56.8/–57.4
	Memorybased DPD	1.96	–57.3/–56.5	–58.5/–59.2
LDMOS PA	Without DPD	44.9	–28.2/–27.9	–47.7/–48.8
	Memoryless DPD	5.54	–53.2/–48.4	–57.3/+53.2
	Memorybased DPD	2.10	–56.8/–57.4	–59.2/–58.6

Conclusion. The study shows that selection and implementation of digital predistortion technique firmly depends on the field of application of these techniques. On the basis of ease of implementation static predistorters might take an edge over adaptation based predistorters, but in real time applications where a PA keep deviating its ideal behavior with respect to the surrounding parameters, adaptation based predistorters should be adopted as a solution. Before choosing any particular adaptive predistortion algorithm a series of measurements and analysis must be conducted to achieve most precise model of a PA. A compromise then can be made between the complexity and affordability to choose a high efficiency nonlinear system and the over consumption of the algorithms capable of linearising the system, to meet the recommendations of different communication standards. In communication systems where uplink recommendations are not very strict, digital predistortion techniques are still used vaguely, but digital predistortion techniques are still finding their way in linearising and rectifying impairments in any nonlinear system.

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