Method for Modeling Amplitude and Bandwidth Dependent Distortion in Nonlinear RF Devices

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Abstract — **A modeling procedure for identifying amplitude and bandwidth dependent distortion in nonlinear RF devices is presented. The modeling mechanism is based on removing the nonlinearity behaviors from the relationship between input-output measurements and applying a linear identification procedure using ARMA models. The model parameters estimation is processed through a non-recursive procedure where an overdetermined set of linear equations is solved analytically employing QR-factorization. Results were carried out for different LDMOS transistor modules at 2.14 GHz. The model fit was in the order of 96%. The method allows the bandwidth dependent distortion to be evaluated under real operating condition by monitoring pole and zero behavior.**

I. INTRODUCTION

The current trend in developing highly linear multi-carrier microwave transmitters with high power efficiency pressures power amplifier designers to focus more on sophisticated circuit topologies, including efficient distortion compensation, e.g. digital predistortion [1]

It is well known that the nonlinearity in RF devices supporting signals with time varying envelopes creates undesirable effects, e.g. intermodulation products, harmonics, and sub-harmonics, that cause interference with the desired modulated signal. The intermodulation products manifest themselves by affecting the quality of the transmitted information within the bandwidth of modulation and also by interfering with adjacent channels. The harmonics and sub-harmonics, although these terms can be eventually filtered out, have a direct impact on the amplitude and phase of the IM products through the intrinsic behavior of the device and circuit interaction. These mechanisms generate new intermodulation products that are amplitude and phase dependent of the fundamental, harmonics and sub-harmonic impedances presented at the device input-output, [2,3].

This phenomenon, known as "*memory effect*", or defined here as bandwidth dependent distortion, is a direct consequence of both the circuit storage elements that shape the modulated signal, and the nonlinearities that generate and mix new spectral components dynamically. The multi-harmonic impedance is not constant over the entire modulation frequency range, and therefore, they present bandwidth limitation influencing the amplitude and phase behaviors of the resulting IM products. A useful method that enables to investigate and evaluate the impact of the multi-harmonic termination at the system level is the two-tone test with varying tone spacing [4]. The limitation is that the time invariant spectrum of the two-tone, including the spacing variation, poorly correlates the time variant spectrum of a digitally modulated signal present at the PA under normal operating conditions. Therefore, it does not reflect an accurate dynamic behavior of the amplitude and bandwidth dependent distortion.

In this paper we propose an efficient method for modeling *amplitude and bandwidth dependent distortion* at system level. We develop a time domain modeling procedure capable of extracting a nonlinear behavior with memory effect in order to evaluate the bandwidth dependent distortion to further optimize the system performance. The modeling mechanism is based on removing the nonlinearity behaviors from the relationship between input-output real-time observations and applying linear identification procedure using ARMA models.

II. CHARACTERIZATION METHODOLOGY

The PA modules are characterized by applying a digitally modulated RF stimulus signal, having a known time dependant phase and magnitude values, to the RF device in order to generate a modulated RF output signal. Both input and output signals are down-converted and digitized in order to establish their instantaneous magnitude and phase as shown Fig.1. The instantaneous magnitude and phase values of both input and output signals are compared to yield the transfer function indicative of the device behavior; see Fig.2 and Fig.3, [5].

The nonlinear amplifier model developed in this work consists of two independent blocks in pipeline form. One represents the memory behaviors and the other the memoryless nonlinearity. A cascade nonlinear model, such as this is known as the generalized Wiener model.

The modeling procedure consists of determining a nonlinear transformation by constructing the inverse nonlinearity function from the measured data and removing the nonlinear effect from the measured output data. To model the memoryless nonlinear function and its inverse, polynomial functions are parameterized by smoothing and fitting the measured data. Then, the memory behavior is extracted by applying a linear identification procedure.

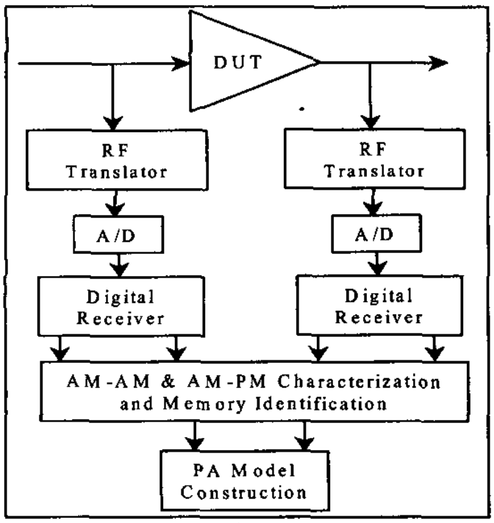

Fig.1

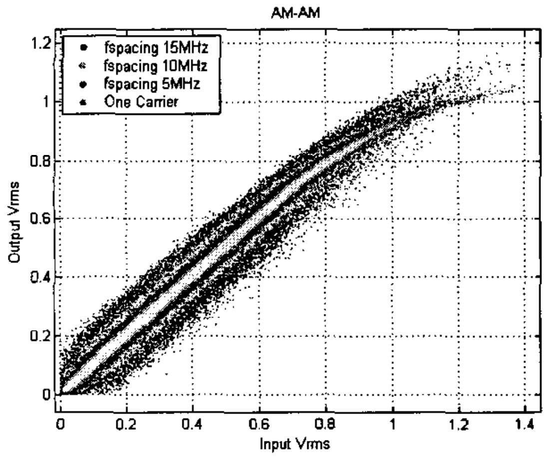

Fig.2

III. DATA PROCESSING

The smoothing estimation is based on a moving average filter, which smoothes the data gathered from a real-time input-output measurement of a 180 W LDMOS module plotted in Fig.4. The plots illustrate the AM-AM characteristics under two-carrier W-CDMA excitation having 10 MHz carriers spacing. In this case, the smoothed data (yellow) is obtained by applying smoothing to the measured data (blue).

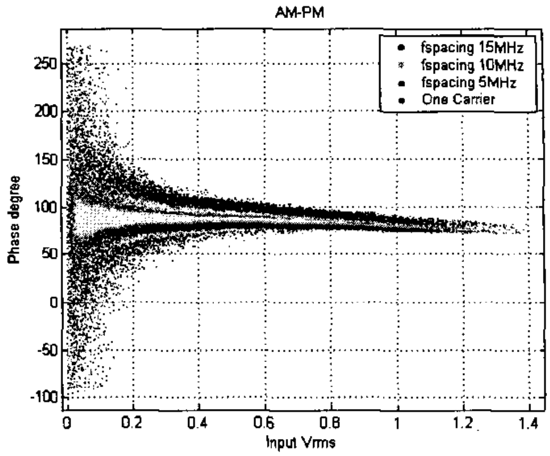

Fig.3

After the data is smoothed, the Minimum Variance Unbiased (MVU) estimator is used to fit the experimental curve with high accuracy [6]. In this algorithm data are observed by using the following model:

$$P_{out} = H\theta + w, \tag{1}$$

where P_{out} is an $N \times 1$ vector of observations, H is a known $N \times p$ observation matrix (with $N > p$) and rank p, θ is a $p \times 1$ vector of parameters to be estimated, and w is an $N \times 1$ noise vector with pdf $N(0, \sigma^2 I)$. By formulizing the observation matrix H as a function of the smoothed data, the MVU estimator is performed straightforward by applying the model expressed as:

$$\hat{\theta} = \left(H^T H\right)^{-1} H^T P_{out} \tag{2}$$

Fig.5 shows the fitting results for the AM-AM characteristics using several polynomial models.

In order to identify and represent the memory behavior through a linear model, the measured data is nonlinearly transformed through a memoryless nonlinear compensation algorithm such as an inverse curve fitting polynomial. Finding the inverse function requires normalizing the curve-fitting polynomial to the linear gain. Then the inverse function can be obtained by curve fitting the inverted data set [5].

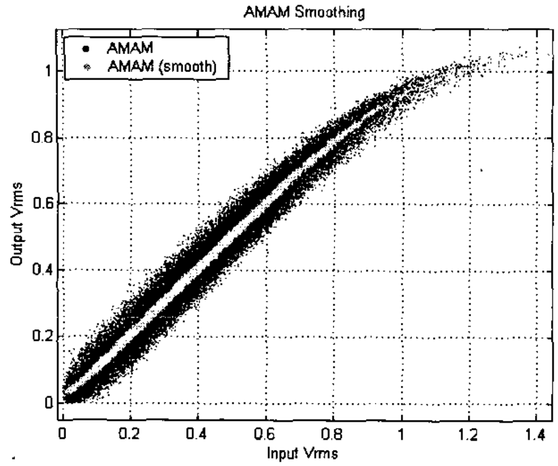

Fig.4

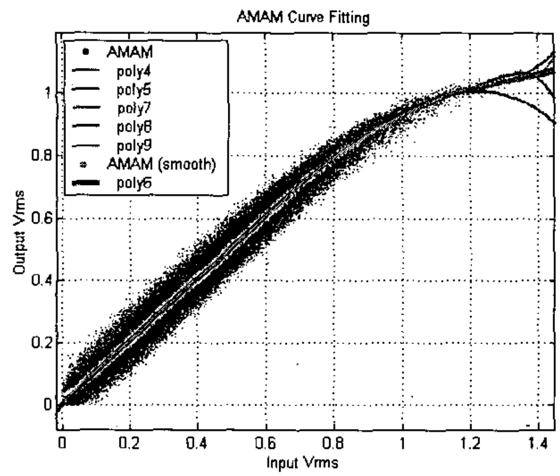

Fig.5

The algorithm identifies the memory behavior by building mathematical models capable of replicating the characteristic related to the linearized data. It implements a set of particular models containing *ARX, ARMAX, OE (Output Error)* and *BJ (Box-Jenkins) model*, which are derived from the following general mathematical formulation:

$$A(q)y(t) = q^{-n_k}\frac{\overline{B}(q)}{F(q)}u(t) + \frac{C(q)}{D(q)}e(t) \qquad (3)$$

where *u(t)* and *y(t)* are the system's input and output at time *t*, *e(t)* is the disturbance of the system, *A, B, C, D, F*, are polynomials describing the properties of the input-output relationships of the model, and q is the delay operator. In general, the dynamics of the model is parameterized in terms of the polynomial coefficients. They are determined by processing the data through a non-recursive procedure where an overdetermined set of linear equations is solved analytically employing QR-factorization [6].

III. RESULTS

Test of the validity was performed by comparing the simulated output from the nonlinear amplifier model and the measured output from the PA when they are run with the same input. The model fit was computed as the percentage of the output difference between modeled and measured time-domain output, $\hat{y} - y$, formulated as follow:

$$\text{model fit} = 100 \times \frac{\left(1 - \text{norm}(\hat{y} - y)\right)}{\text{norm}(y - \text{mean}(y))} \qquad (4)$$

Table I shows validation results in percentage for the four models related to the number of taps for each polynomial. In addition, Model validation was evaluated by inspecting the model's ability in reproducing the PA behaviors in time and frequency domain. Fig.6 and Fig.7 show the time domain evaluation of the ARX model. The results reveal a good agreement between the simulated output and the measured output waveform. The simulated output waveform for the other mathematical models show similar results. Fig.8 shows the output spectrum of both simulated and measured output. Also, the spectrum of the input signal is included as a reference.

Table I

# of taps	2	3	4	5	6
ARX	95.99	96.05	96.05	96.05	95.97
ARMAX	96.00	96.06	96.06	96.06	96.01
OE	96.03	96.08	96.08	96.09	
BJ	96.01	96.06	96.06	96.02	

An interesting way to visualize the dynamics of the memory behavior is through the pole and the zero observation. The poles and the zeros are equivalent ways of describing the coefficients of the linear difference equation, and their locations completely determine the envelope transfer function, which represent the memory behavior. In Fig.9 we can visualize the pole and the zero positions of I-filter for six different timeslot, in Z domains, sequentially of the data. The plots clearly reveal the variation of the poles and zeros in time. It is a direct consequence of the PA dynamic behavior.

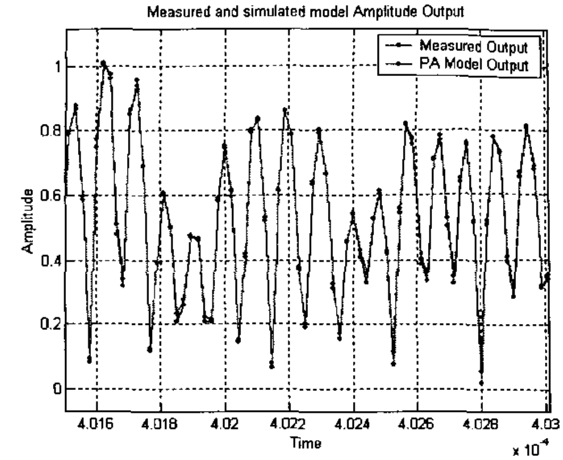

Fig.6

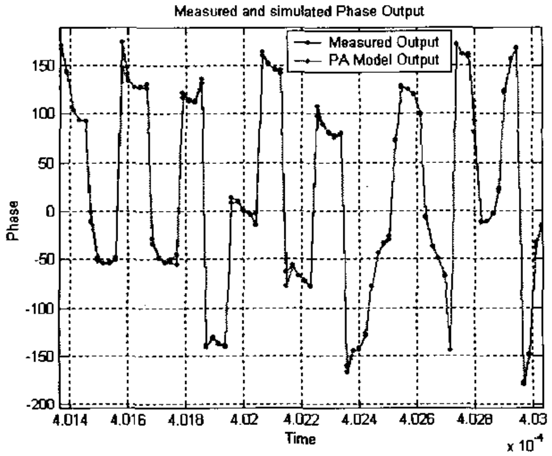

Fig.7

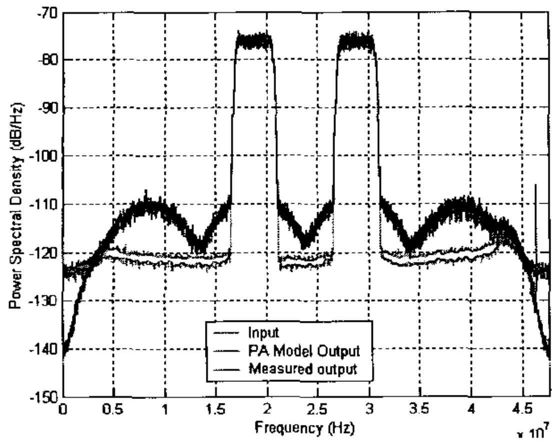

Fig.8

V. CONCLUSION

An efficient method for modeling dynamic behavior of *amplitude and bandwidth dependent distortion* has been proposed. The method demonstrates that linearity tests and modeling using stimulus signals similar to real condition digitally modulated signals, is an accurate characterization method that can reflect the amplifier behavior under normal operating conditions. The model fit was in the order of 96%. The method allows the bandwidth dependent distortion to be evaluated under real operating condition by monitoring dynamic poles and zeros of the envelope transfer function of a PA.

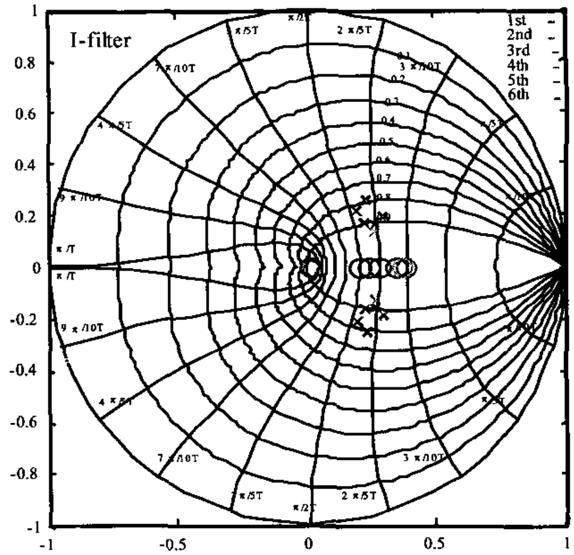

Fig 9

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