Extraction of Accurate Behavioral Models for Power Amplifiers with Memory Effects using Two-tone Measurements

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***Abstract*—This paper proposes a system-level behavioral model for RF power amplifiers (PAs) that exhibit memory effects. PAs with memory effects are shown to have two-tone intermodulation distortion (IMD) levels that vary depending on tone-spacing. Thus, typical single tone extracted AM/AM and AM/PM characteristics cannot accurately model PAs memory effects. By varying the frequency spacing of two-tone signals, envelope frequency dependent transfer functions can be derived. Using these transfer functions, a behavioral model is developed which is based on the parallel-cascade linear and nonlinear (LN) system. This model gives more accurate results in predicting behavior of PAs with memory effects close to the carrier frequency. The model is validated by comparing the predicted and the measured adjacent channel power ratio (ACPR) of a CDMA signal amplified by a high power class-AB PA. It is found that the parallel cascade model improves ACPR prediction accuracy by as much as 4 dB compared to the single tone derived memoryless model.**

I. Introduction

In wireless communications, the transmitter power amplifier (PA) introduces nonlinearities when it operates near maximum output power. In system level simulation, behavioral models are often employed to model the PA nonlinearities. These measurement-based empirical models provide a computationally efficient means to relate input complex envelope to output complex envelope without resorting to physical level analysis of the PA. Behavioral models for PAs can be classified into three categories depending on the existence of memory effects [1][2][3]: memoryless nonlinear systems, quasi-memoryless nonlinear systems, and nonlinear systems with memory. For the memoryless nonlinear system, the PA block is represented by the narrowband AM/AM transfer function. For the quasi-memoryless nonlinear system, with memory time constants on the order of the period of the RF carrier, the PA block is often represented by AM/AM and AM/PM functions. Usually, AM/AM and AM/PM are measured by sweeping the power of single-tone in the center frequency of the pass band of the RF PA. For a nonlinear system with long-term memory effects, on the order of the period of the envelope signal, the system response depends on not only input envelope amplitude but also its frequency. In [4], the high power amplifier (HPA) with memory effects shows that the two-tone intermodulation distortion (IMD) depends on tone spacing. It is shown in [4] that the application of a memoryless baseband predistortion algorithm gives significant improvement in adjacent channel power ratio (ACPR) to 0.5W handset PA. However, the same algorithm cannot significantly improve the nonlinearity of 45W base station PA, which is shown to exhibit memory effects. Because predistortion methods depend heavily on the accuracy of the PA model, memoryless AM/AM and AM/PM are not sufficient to describe HPAs with memory effects. A nonlinear system with memory can be represented by Volterra series, which are characterized by Volterra kernels[3]. However, the computation of the Volterra kernels of nonlinear system is often difficult and time-consuming for strongly nonlinear devices. In many applications involving modeling of nonlinear systems, it is convenient to employ a simpler model. The cascade connection of linear time invariant (LTI) system and memoryless nonlinear system has been used to model the nonlinear PA with memory[1][5][6][7][8]. In this case, frequency dependent memoryless nonlinear model yield identical shape but only gives shift with reference AM/AM, AM/PM curves[9]. However, these models are not sufficient to identify modulated signals including two-tone signals.

In this paper, we propose a more accurate model based on the parallel cascade linear-nonlinear (LN) model developed by Schetzen[3]. Using two-tone signals, AM/AM and AM/PM curves are extracted for each envelope frequency by measuring IMD products. From the data, optimal filter functions and nonlinear transfer characteristics for each parallel branch are then derived. In this way, long time constant memory effects may be modeled with a long delay LTI system in a parallel branch.

II. AM/AM, AM/PM and Two-tone Response

A memoryless PA can be modeled with AM/AM and AM/PM. The input signal $v(t)$ can be described as

$$v(t) = \text{Re}\{g(t)e^{j\omega_c t}\} = r(t)\cos(\omega_c t + \theta(t)) \qquad (1)$$

where $g(t)$ is complex envelope of baseband input signal, ω_c is the carrier center frequency, $r(t)$ is the amplitude of $g(t)$ and $\theta(t)$ is the phase of $g(t)$. The AM/AM and AM/PM can be represented with complex polynomial transfer func-

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tion[10][11];

$$F(r) = a_1 r + a_3 r^3 + \cdots + a_{2n-1} r^{2n-1} = \sum_{k=1}^{n} a_{2k-1} r^{2k-1} \quad (2)$$

where a_{2k-1} are complex coefficients. Only the odd terms are needed to determine in-band and adjacent channel interference. The output signal $w(t)$ can be described as

$$\begin{aligned} w(t) &= \mathrm{Re}\{F(r(t))e^{j\theta(t)}e^{j\omega_c t}\} \\ &= R(t)\cos(\omega_c t + \theta(t) + \Psi(t)) \end{aligned} \quad (3)$$

where $R(t)$ is the amplitude of $F(r(t))$, and $\Psi(t)$ is the phase of $F(r(t))$, which are AM/AM and AM/PM characteristic functions respectively. If the two-tone output response has the almost symmetric IMD characteristic, AM/AM and AM/PM can be directly related with the two-tone response and vice versa. The two-tone input which has magnitude $A/2$ and phase $\varphi(t)$ for each tone, and has the tone space $2\omega_m$, can be described as

$$\begin{aligned} v(t) &= \frac{A}{2}\Big[\cos\big((\omega_c - \omega_m)t + \varphi(t)\big) + \cos\big((\omega_c + \omega_m)t + \varphi(t)\big)\Big] \\ &= A\cos(\omega_m t)\cos(\omega_c t + \varphi(t)) \end{aligned} \quad (4)$$

For this two-tone input, the complex envelope, $g(t)$, is $A\cos(\omega_m t)e^{j\varphi(t)}$. If $F(r(t))e^{j\theta(t)}$ is defined as $y(t)$, then the output complex envelope, $y(t)$, can be acquired as follows;

$$\begin{aligned} y(t) &= \sum_{k=1}^{n} a_{2k-1}A^{2k-1}\cos(\omega_m t)^{2k-1}e^{j\varphi(t)} \\ &= \sum_{k=1}^{n} d_{2k-1}\cos((2k-1)\omega_m t)e^{j\varphi(t)} \end{aligned} \quad (5)$$

where

$$d_{2k-1} = \sum_{i=k}^{n} \frac{{}_{2i-1}C_{i-k}}{4^{i-1}} a_{2i-1}A^{2i-1} \quad (6)$$

Thus the PA output $w(t)$ for the two-tone input can be acquired using (3) and (5);

$$\begin{aligned} w(t) &= \mathrm{Re}\{y(t)e^{j\omega_c t}\} \\ &= \sum_{k=1}^{n} |d_{2k-1}|\cos((2k-1)\omega_m t)\cos(\omega_c t + \varphi(t) + \angle d_{2k-1}) \\ &= \sum_{k=1}^{n} \frac{|d_{2k-1}|}{2}\cos(\omega_c t \pm (2k-1)\omega_m t + \varphi(t) + \angle d_{2k-1}) \end{aligned} \quad (7)$$

Fig.1 shows an illustration of the two-tone output resulting from (7). From (7), if the two-tone output characteristics are measured for input signals which have the different magnitude $A_1, ..., A_l$, the coefficients, $d_{2k-1,1}, ..., d_{2k-1,l}$ ($k = 1, ..., n$), for each input signal can be acquired. The complex coefficient in (2) can be derived to minimize the error function;

$$\min \sum_{k=1}^{n}\sum_{q=1}^{l} \lambda_k \kappa_q \left| d_{2k-1,q} - \sum_{i=k}^{n} \frac{{}_{2i-1}C_{i-k}}{4^{i-1}} a_{2i-1}A_q^{2i-1} \right|^2 \quad (8)$$

where κ_q is weighting factor depending on input power and λ_k is weighting factor depending on output frequency.

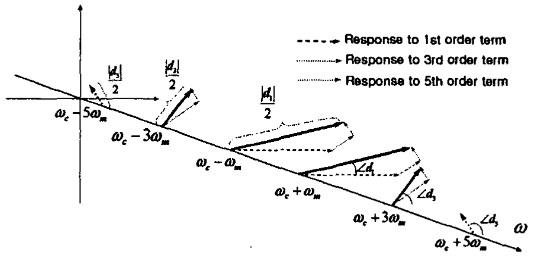

Fig. 1. An illustration of the two-tone output of a nonlinear device showing the relative phases of the IMD products

III. Modeling of PA with Memory

By sweeping envelope frequency ω_m, the frequency dependent coefficient $a_{2k-1}(\omega_m)$ can be derived. Thus, the two-tone characteristic function considering memory effects can be described as

$$\begin{aligned} F(r, \omega_m) &= a_1(\omega_m)r + a_3(\omega_m)r^3 + \cdots + a_{2n-1}(\omega_m)r^{2n-1} \\ &= \sum_{k=1}^{n} a_{2k-1}(\omega_m)r^{2k-1} \end{aligned} \quad (9)$$

The frequency dependent complex polynomial can be realized by parallel cascade structure of LTI system connected in series with memoryless nonlinear system as shown in Fig.2.

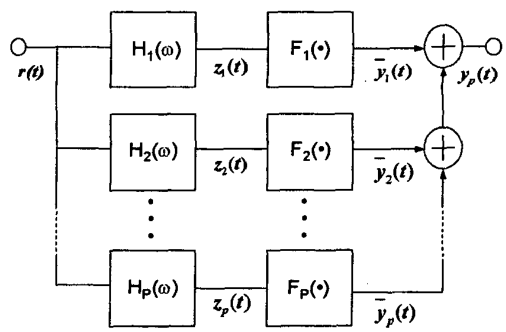

Fig. 2. PA Model for a system with memory using parallel cascade LN model

This model is simpler than general Volterra system models, but has been shown to approximate memory effects well in other nonlinear systems[12]. The LTI system has the characteristic function as follows;

$$H_i(\omega_m) = |H_i(\omega_m)|e^{j\Omega_i(\omega_m)} \quad (10)$$

$F_i(\cdot)$ is the complex polynomial with the coefficient $a_{2k-1,i}$ ($k = 1, \cdots, n, i = 1, \cdots, p$). The output for the parallel cascade LN system is

$$\begin{aligned} y_p(t) &= \sum_{i=1}^{p} \bar{y}_i(t) = \sum_{i=1}^{p} F_i(z_i(t)) \\ &= \sum_{i=1}^{p} \sum_{k=1}^{n} a_{2k-1,i}\left(A|H_i(\omega_m)|\cos(\omega_m t+\Omega_i(\omega_m))\right)^{2k-1} \end{aligned} \quad (11)$$

where p is the number of the parallel branch, $z_i(t)$ is the output for LTI system of the ith branch, and $\bar{y}_i(t)$ is the output for nonlinear system of the ith brach. In (11), $a_{2k-1,i}, H_i(\omega_m)$, can be acquired to minimize mean square error $\overline{\varepsilon_i^2}$, where

$$\varepsilon_i = y(t) - y_i(t) = y(t) - \sum_{k=1}^{i} \bar{y}_k(t), \ (i = 1, \cdots, p) \quad (12)$$

The mean square error $\overline{\varepsilon_i^2}$ can be expressed in a recursive form

$$\begin{aligned} \overline{\varepsilon_i^2} &= \overline{(\varepsilon_{i-1} - \bar{y}_i)^2} \\ &= \overline{\varepsilon_{i-1}^2} + \overline{\bar{y}_i^2} - 2\mathrm{Re}\{\overline{\varepsilon_{i-1}\bar{y}_i^*}\} \end{aligned} \quad (13)$$

Parameter estimation of the nonlinear parallel system has been developed[13][14]. The parameter identification procedure for parallel cascade PA model can be outlined as follows: The first branch of system is set to memoryless model, thus the linear system, $H_1(\omega_m)$, has time response $h_1 = \delta(t)$ and the nonlinear system, $F_1(\cdot)$, has AM/AM and AM/PM response. Linear system $H_i(\omega_m)$, $(i = 2, \cdots, p)$ can be acquired using the cross-correlation function of the input $r(t)$ and the error ε_{i-1}. The coefficients $a_{2k-1,i}$, $k = (1, \cdots, n)$ of the $F_i(\cdot)$, $(i = 2, \cdots, p)$ are determined to minimize the mean square error $\overline{\varepsilon_i^2}$ in (13) for the input $z_i(t)$. The branches are added until $\overline{\varepsilon_i^2}$ is less than threshold value.

IV. Experimental Validation

For the experimental validation, two-tone output was measured versus tone-space (0kHz∼1500kHz) and input power (-15dBm∼3dBm) for the Ericsson 45W base station PA shown in Fig.3. The operating frequency of this silicon BJT-based class-AB PA is 885MHz. The design was intended for use with constant envelope (AMPS) signals, and hence, it exhibits strong memory effects for amplitude modulated signals. The measured fundamental, IM3, and IM5 amplitude response for several tone spacings are plotted in Fig.4. This amplifier showed almost symmetric IMD response, thus each fundamental, IM3, and IM5 was acquired by averaging amplitude of upper and lower terms.

In Fig.4, the two-tone output shows some variation depending on two-tone spacing, which results from memory effects. Using (8), the amplitude transfer function, which depends on envelope frequency and input power, was acquired and plotted in Fig.5. In (8), the weighting factor was set to unity. In the unit under test, it was found

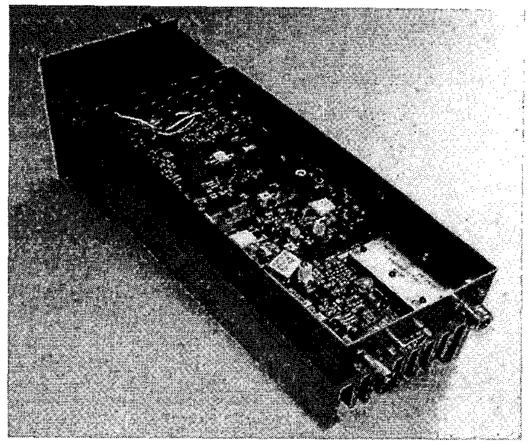

Fig. 3. Ericsson 45W Base Station Power Amplifier

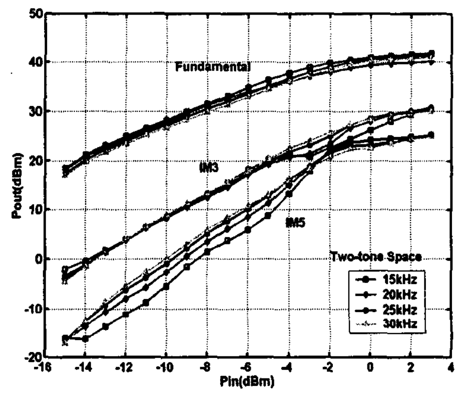

Fig. 4. Two-tone measurements with varying tone-spacing

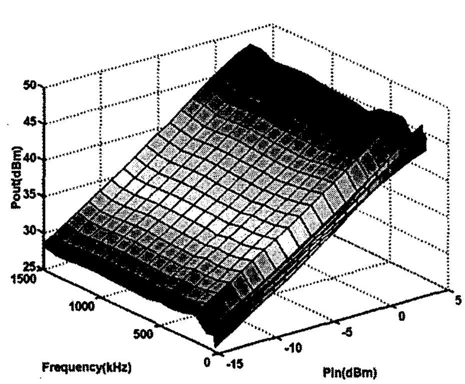

Fig. 5. Derived AM/AM response versus tone-spacing

that AM/PM effects only had a negligible effect on the close-in ACPR. Thus, to simplify the extraction procedure, AM/PM effects were ignored. To model this PA, a parallel cascade LN model was used, which consists of fifth order nonlinear memoryless model and four parallel branches. Using some calculation, $H_i(\omega_m)$ and $F_i(\cdot), (i = 1, \cdots, 4)$ can be acquired.

The adjacent channel power ratio (ACPR) was predicted for an IS-95 CDMA signal with 46.9dBm output power. This is compared to the measured results in Fig.6. The output from the parallel cascade LN model is also compared to a conventional AM/AM model. It is seen that the parallel cascade LN model, which was acquired from two-tone measurements gives more accurate ACPR results than the AM/AM model by a much as 4 dB for close-in ACPR.

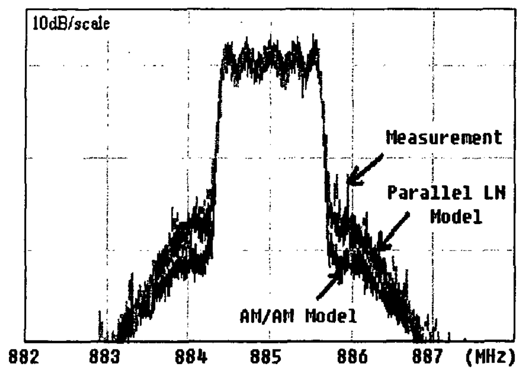

Fig. 6. Predicted and Measured ACPR for CDMA Signal

V. Conclusion

In this paper, we propose an accurate behavioral model for RF PAs that exhibit strong memory effects. The long time constant memory effect is identified by measuring the variation in output two-tone IMD versus two-tone spacing. This set of measurements maps out a two-dimensional transfer function that depends on envelope frequency and amplitude of a two-tone signal. The frequency dependent transfer functions are then fit to a parallel cascade LN model, which is a special case of the full Volterra series. Because long time constant memory effects may be included in parallel branches, PA models using the parallel cascade LN model can give a more accurate prediction for the output two-tone IMD amplitude and phase variation versus envelope frequency due to the memory effects. The model derived from two-tone measurements was also validated by comparing the predicted ACPR for an IS-95 CDMA signal to the measured result. It was seen that the model predicted ACPR well. The model was also compared to a memoryless model derived from single-tone measurements. It was seen that the inclusion of memory effects afforded by the parallel-cascade LN model improved the accuracy of close-in ACPR prediction by as much as 4 dB.

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