MODELING AND COMPENSATING MEMORY EFFECT IN HIGH POWER AMPLIFIER FOR OFDM SYSTEMS

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Abstract—This paper is concerned with a new time-domain modeling topology for signals which is applied to OFDM systems. This model is a more accurate based on Wiener approach. Also the memory effect will be shown using two-tone intermodulation distortion (IMD) measurement with different tone frequency spacing and power levels. Next adaptive predistorter to counterbalance the AM/AM and AM/PM nonlinear effects of the transmitter power amplifier is proposed by Hammerstein approach. Finally we consider the effectiveness of proposed method on performance of OFDM signal as the wideband system by reduction of distortion. It is confirmed by computer simulation that proposed approach produces a faster convergence speed than the previous adaptive predistortion technique.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is currently under significant investigation due to a high spectral efficiency and immunity to multipath fading and impulse noise. Usage of an appropriate guard interval in OFDM can easily prevent intersymbol interference (ISI) and interchannel interference (ICI), whereas powerful equalization techniques are required for single carrier modulation. However, OFDM-based systems are subject to be significantly sensitive to nonlinear distortion, usually caused by a high power amplifier [1–3].

High RF power amplifier characterization and modeling has been a subject of study over the last few years. This is mainly driven by the need of a precise behavioral model, which represents the nonlinearity of the high power amplifiers (HPAs) and linearizers. The power amplifier is often represented by nonlinear amplitude (AM/AM) and phase (AM/PM) functions in either polar or quadrate form [4–6]. These measurement-based empirical models provide a

computationally efficient means to relate the input complex envelope to the output complex envelope without resorting to a physical level analysis of the PAs. Behavioral models for PAs can be classified into three categories depending on the existence of memory effects [7–9]: memoryless nonlinear systems, quasi-memoryless nonlinear systems, and nonlinear systems with memory. For the memoryless nonlinear system, the PA block is represented by the narrow-band 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 a single tone in the center frequency of the passband 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 not only on the input envelope amplitude, but also its frequency. An alternate view is that the AM/AM and AM/PM functions appear to change as a function of past input levels. Such effects may arise in high power amplifiers (HPAs) from thermal effects, as well as long time constants in dc-bias networks.

A nonlinear system with memory can be represented by Volterra series, which are characterized by Volterra kernels [8]. However, the computation of the Volterra kernels for a nonlinear system is often difficult and time consuming for strongly nonlinear devices. In many applications that involve modeling of nonlinear systems, it is convenient to employ a simpler model. The Wiener model, which is cascade connection of linear time invariant (LTI) system and memoryless nonlinear system, has been used to model nonlinear PAs with memory [7, 10–16]. The Wiener model that is frequency-dependent memoryless nonlinear model yields identical shape, but only creates a shift with reference AM/AM and AM/PM curves [17].

In order to reduce performance degradation in OFDM systems, compensation of nonlinear distortion is required. Several prefiltering techniques for a memoryless nonlinear system, preceded by a linear system, have been reported [18, 19].

In this paper, we propose a more accurate model based on the Wiener model developed by Schetzen [8].

Using two-tone signals, AM/AM and AM/PM curves are extracted for each envelope frequency by measuring IMD products. The derivation of the AM/AM and AM/PM complex function from two-tone measurement is proposed in Section 2. The adaptive modeling of a PA with memory effects for OFDM signal is described in Section 3. An adaptive nonlinear predistorter in an OFDM system is proposed in Section 4 [20].

2. AM/AM AND AM/PM AND TWO TONE RESPONSE

A bandpass input signal of a PA can be represented as (1),

$$v(t) = \operatorname{Re}\left\{g(t)e^{j\omega_c t}\right\} = r(t)\cos(\omega_c t + \theta(t)) \tag{1}$$

Where $g(t)$ is the input complex envelope signal, ω_c is the carrier center frequency, $r(t)$ is the amplitude of $\theta(t)$, and is the phase of $g(t)$.

The nonlinear device such as a PA is usually represented by Power series of input signal, the bandpass output signal of the PA $w(t)$, which consists of $(2n-1)$th-order of power series, can be described as follows:

$$w(t) = \operatorname{Re}\left\{f(t)e^{j\omega_c t}\right\}$$
$$f(t) = \sum_{k=1}^{n} \alpha_{2k-1}|g(t)|^{2(k-1)}g(t) = \sum_{k=1}^{n} \alpha_{2k-1}r(t)^{2k-1}e^{j\theta(t)}. \tag{2}$$

In (2), the odd order complex power series is defined as

$$F(r(t)) = \sum_{k=1}^{n} \alpha_{2k-1}r(t)^{2k-1} \tag{3}$$

AM/AM and AM/PM characteristic functions can then be jointly represented by $F(r(t))$ as follows:

$$w(t) = |F(r(t))|\cos(\omega_c t + \theta(t) + \angle F(r(t))) \tag{4}$$

Using the complex envelope $f(t)$, 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, which tone spacing $2\omega_m$, can be described as:

$$v(t) = \frac{A}{2}[\cos((\omega_c - \omega_m)t + \varphi(t)) + \cos((\omega_c + \omega_m)t + \varphi(t))]$$
$$= A\cos(\omega_m t)\cos(\omega_c t + \varphi(t)) \tag{5}$$

For this two-tone input, the complex envelope $g(t)$ is $A\cos(\omega_m t)e^{j\varphi(t)}$. The output complex envelope $f(t)$ can then be acquired as follows:

$$f(t) = \sum_{k=1}^{n} \alpha_{2k-1}A^{2k-1}\cos^{2k-1}(\omega_m t)e^{j\varphi(t)} \tag{6}$$

From (6) can be shown that the coefficients are dependent of frequency.

For the experimental validation, two tone output was measured versus tone spacing (2–20 MHz) and input power level, it exhibits memory effect. The third order intermodulation distortion (IMD) of the DUT is plotted in Fig. 1. the PA versus frequency and output power level is quite variable, which result from memory effect.
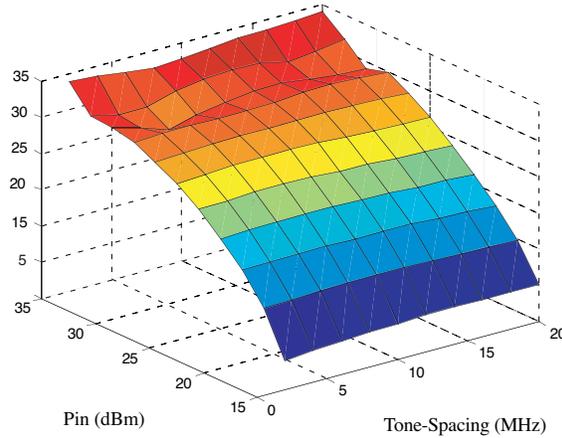
Figure 1. IMD3 versus tone spacing and power input.

3. ADAPTIVE DEVELOPMENT OF PA IN AND OFDM SYSTEM

A primitive block diagram of the OFDM transmission system is shown in Fig. 2. The serial-to-parallel block converts a QAM input data stream to a block of N symbols, which modulates the corresponding subcarrier. To cancel the ISI and the ICI after OFDM modulation which is done by the IFFT, the guard interval that is longer than the largest delay spread is inserted. The linear filter in Figure 2 represents the transmitter pulse shaping filter usually placed at the baseband or at the IF stage. From Fig. 2, it can be seen that a Solid State PA (SSPA) preceded by a linear filter can be well modeled by the Wiener system, which consists of a memoryless nonlinear subsystem preceded by a linear dynamic subsystem [21].
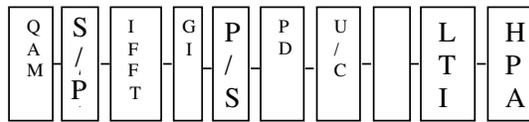

Figure 2. A simplified block diagram of an OFDM transmitter.

The block diagram of the proposed Wiener system and adaptive predistorter, is shown in Figure 3. The proposed scheme is composed of a system estimator that estimates the parameters of the Wiener system using an adaptive algorithm, and an adaptive predistorter that compensates nonlinearity effects.
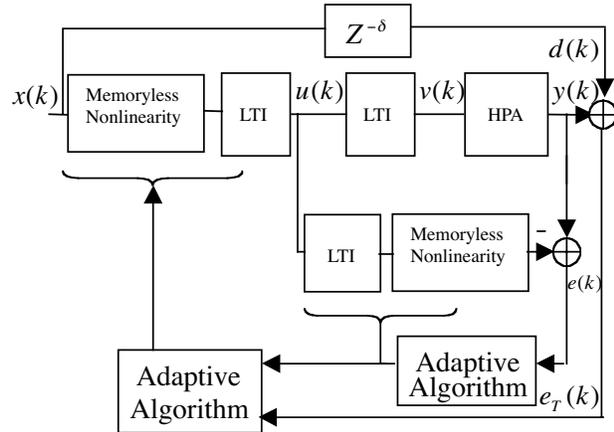
Figure 3. An adaptive predistorter for the HPA preceded by a linear filter.

If the SSPA can be approximated by a polynomial form of finite order, the input and output relationship of the system is given by

$$y(k) = \sum_{p=1}^{P} \gamma_p \cdot v(k)^p \qquad (7)$$

$$v(k) = \sum_{n=0}^{N} \beta_n x(n-k) \qquad (8)$$

Where N and P respectively, denote the memory length of the linear filter, and the order of the nonlinear filter. Also, $x(n)$ denotes the input signal of the linear filter. Using only the input and output signals of the system, the coefficients of the system estimator, γ_p and β_n, are adjusted to minimize the mean square error, $E\{|e(k)|^2\}$ between y and y_{meas}.

$$y(k) = \sum_{p=1}^{P} \gamma_p \cdot \left(\sum_{n=0}^{N} \beta_n x(n-k) \right)^p \qquad (9)$$

But as it can be deduced from eq. (9), an easy linear regression of its coefficients it is not possible since the filter coefficients are integrated in the power series. In order to solve this problem, it is possible to first estimate the intermediate variable $v(k)$, as it is proposed in [22], for later divide the estimation problem into two steps. To estimate the intermediate variable, it is necessary to use the following assumptions [22]: a) the linear subsystem (the FIR filter) is stable, b) the nonlinear

function (polynomials) is invertible, and c) there is no noise in the system. Assuming this, it is possible to calculate the intermediate variable as described in eq. (10),

$$v(k) = \sum_{n=0}^{N} \beta_n x(n-k) = \sum_{p=1}^{P} \xi_p \cdot y(k)^p \tag{10}$$

So then, eq. (10) describes an equation where the parameters come in linearly and thus can be estimated by linear regression. The error that wants to be minimized is described in eq. (11), where to avoid the trivial solution $(\gamma, \beta = 0)$, it is possible to fix one parameter without loss of generality due to the over parameterization [13]. Since it can be used normalized data we fix $\xi_1 = 1$.

$$e(k) = y(k) - \left(\sum_{p=2}^{P} \xi_p y(k)^p - \sum_{n=0}^{N} \beta_n x(k-n) \right) \tag{11}$$

$$e(k) = y(k) - \eta_k \cdot g_k \tag{12}$$

Where,

$$\eta_k = [\xi_2, \ldots, \xi_P, \beta_0, \beta_1, \ldots, \beta_N]$$
$$g(k) = [y(k)^2, \ldots, y(k)^P, x(k), x(k-1), \ldots, x(k-N)]$$

Once the quadrative criterion $\{\min \sum_{k=1}^{l} (e(k))^2\}$ is minimized, the intermediate variable $v(k)$ is available as follows

$$\eta_{k+1} = \eta_k - \mu_\eta \frac{\partial |e(k)|^2}{\partial \eta_k} \tag{13}$$

Where μ_η represents the step-size constant of η_k and it controls stability and the convergence speed of the algorithm. So the normalized updating equation as follows:

$$\eta_{k+1} = \eta_k + \mu_\eta \frac{e(k)^* \cdot g_k}{\varepsilon + |g_k|^2} \tag{14}$$

Considering eq. (14) parameters which are needed for knowing the output data can be derived.

4. AN ADAPTIVE NONLINEAR PREDISTORTER IN AN OFDM SYSTEM

Considering the nonlinearity compensator section, an adaptive predistorter, which is ideally the inverse of the Wiener system, can

be designed. The usual inverse structure of the Wiener system is the Hammerstein model [23]. As it can be seen the predistorter in Figure 3 is constructed by a memoryless nonlinear inverse filter cascaded by a linear inverse filter. By using a polynomial form of finite order as the memoryless nonlinear inverse filter, the predistorter can be expressed as

$$u(k) = \sum_{m=0}^{M} \lambda_m \sum_{q=1}^{Q} \alpha_q x^q(k-m) \tag{15}$$

Where M denotes the memory length of the linear inverse filter λ_m, and Q denotes the order of the nonlinear inverse filter α_q.

$$v(k) = \sum_{n=0}^{N} \beta_n \left(\sum_{m=1}^{M} \lambda_m \left(\sum_{q=1}^{Q} \alpha_q x^q(k-m-n) \right) \right) \tag{16}$$

$$v(k) = \beta_k \cdot C_k^T \cdot R_k \tag{17}$$

Where

$$C_k = [\lambda_0 \alpha_1, \ldots, \lambda_0 \alpha_Q, \lambda_1 \alpha_1, \ldots, \lambda_1 \alpha_Q, \ldots, \lambda_m \alpha_Q]$$

$$R_k = [r_k, r_{k-1}, \ldots, r_{k-N}]$$

$$r_k = [x(k), \ldots, x^Q(k), x(k-1), \ldots, x^Q(k-1), \ldots, x^Q(k-M)]$$

$$R_k = \begin{bmatrix} x(k) & x(k-1) & \cdots & x(k-N) \\ \vdots & \vdots & \vdots & \vdots \\ x^Q(k-M) & x^Q(k-1-M) & \cdots & x^Q(k-N-M) \end{bmatrix}$$

The error of the total system is defined by

$$e_T(k) = v(k) - \beta_k C_k^T R_k \tag{18}$$

To update the coefficients C_k we apply an adaptive method like the previous section as follows

$$C_{k+1} = C_k - \mu_c \nabla_{c_k} |e(k)|^2 \tag{19}$$

$$C_{k+1} = C_k + \frac{\mu}{\varepsilon + |R_k \cdot \beta_k|^2} e^*(k) \cdot R_k \cdot \beta_k \tag{20}$$

The error of the total system is defined by

$$e_T(k) = d(k) - y(k) \tag{21}$$

where the desired signal $d(k)$ is the delayed version of the input signal $x(k)$ by δ samples to account for causality of the predistorter.

5. COMPUTER SIMULATION

In this section, a computer simulation is used to demonstrate the validity of the proposed PA model and the predistortion technique for compensation of a class-A PA designed with the Agilent ATF-34143 PHEMT transistor. The serial-to-parallel converter transfers a block of 1024 16-QAM symbols to the OFDM modulator. For close examination of the effectiveness of the predistorter in compensating the nonlinear distortion, it was assumed that the multipath fading effect is completely compensated, resulting in an additive white Gaussian noise (AWGN) channel. The parameters of the Wiener system, the SSPA preceded by the linear filter, were first estimated by the system estimator. The order of the memoryless nonlinear part of the PA, N, in the system estimator was set to five in the system estimator was set to five in order to model only significant nonlinear distortions of SSPA with a minimal number of parameters. The memory length of the linear filter, P, was set to three. Figure 4(a) shows the value of MSE for different iteration number that results a very fast convergence with proposed method. We choose 50 iteration number for investigating the performance of the OFDM system The PA parameters were updated simultaneously using the stochastic gradient method. Also the step-size constants, which determine convergence speed and MSE after convergence, were set to 0.09 for the linear filter and 0.1 for the nonlinear filter. With zero initial condition, about 263.3 dB in the MSE was obtained, resulting in a fairly accurate estimation of filter coefficients for the Wiener system under test in comparing [24].

After having checked the convergence of the MSE in the system estimator, the proposed adaptive algorithm was applied to obtain filter coefficients of the predistorter. The order of the nonlinear inverse filter, M, and the memory length of the linear inverse filter, Q, in the predistorter were set to numbers large enough to model inverse functions, seven and ten, respectively. Again Figure 4(b) shows the value of MSE for different iteration number for predistorter. The step-size constant for predistorter was set to 0.02. The consequence convergence of MSE to -67.13 for 50 numbers of iteration which was tradeoff between speed and accuracy, signifies that the proposed adaptive predistorter is effective in compensating the linear and nonlinear distortion present in the Wiener system even with a small number of filter taps. As it can be observed in Figure 5, the output spectrum of the OFDM signal provided by the wiener model resemble the real PA output power spectrum exactly.

Figure 6 shows the performance achieved by the Hammerstein based predistorter.
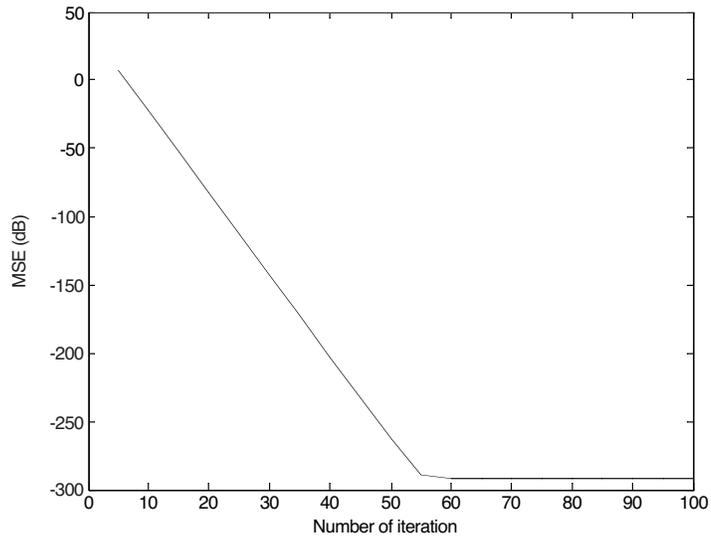
(a)
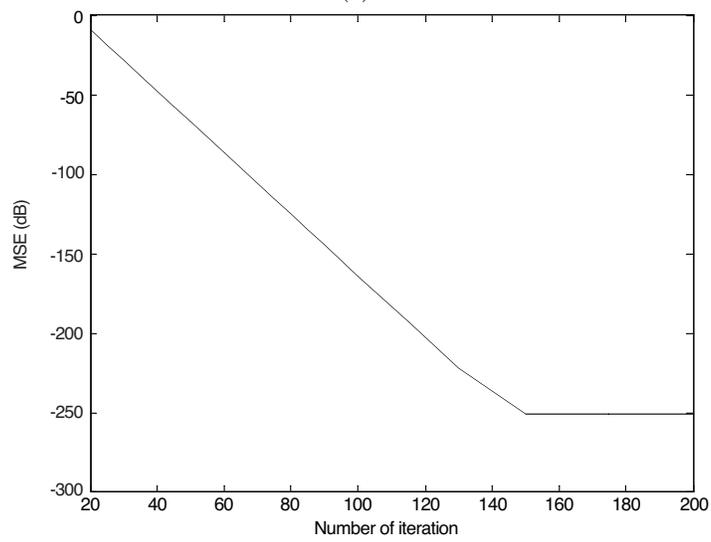
(b)

Figure 4. a) system estimator ($N = 3$, $P = 5$) and (b) predistorter ($M = 7$, $Q = 10$); Output backoff $= 4$ dB.
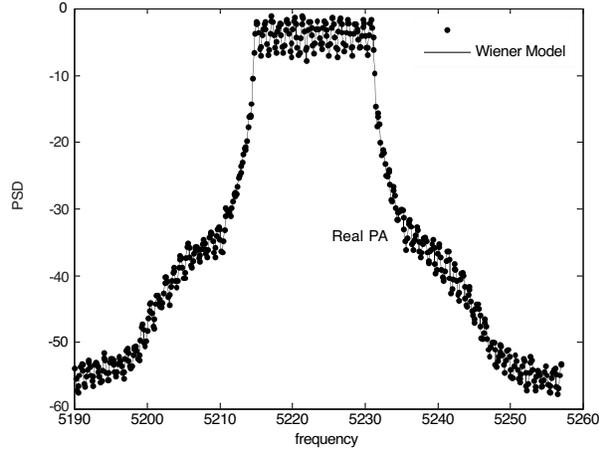
Figure 5. Output power spectra of an OFDM signal for: a real PA, a wiener based PA model (Output backoff = 4 dB).
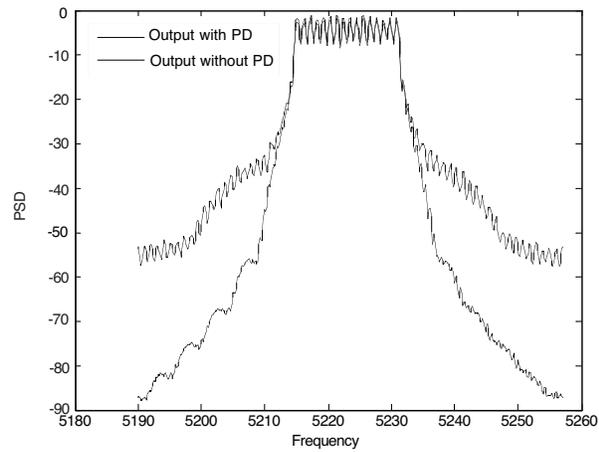

Figure 6. Output power spectra of an OFDM signal with and withput PD.

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