Hammerstein predistorter for High Power RF Amplifiers in OFDM Transmitters

Tahereh Sadeghpour*[1], *Haleh Karkhaneh*[2], *Raed Abd-Alhameed*[1], *Ayaz Ghorbani*[2], *I.T.E.Elfergani*[1], *Y.A.S. Dama*[1]

[1]School of Engineering, Design and Technology, Bradford University Bradford, BD7 1DP, UK;
E-mail: tsadeghp@brad.ac.uk, R.A.A.Abd@brad.ac.uk, i.t.e.elfergani@brad.ac.uk, y.a.s.dama@bradford.ac.uk,
[2] Departments of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran;
E-mail: h_karkhane@aut.ac.ir, ghorbani@aut.ac.ir

Abstract

OFDM (Orthogonal Frequency-Division Multiplexing) is a wideband digital modulation scheme which is critically dependent on linearity in the hardware system, due to its reliance on Fourier Transformation and its inherently high peak-to-average power ratio (PAPR), and minimization of nonlinearity is thus a priority. In this paper the effectiveness of a predistortion based on the Hammerstein model dealing with the nonlinear response is investigated by measurement of Error Vector Magnitude (EVM) in AWGN channel and Adjacent Channel Power Ratio (ACPR). Accuracy of prediction of Power Amplifier (PA) nonlinearity with memory effect and baseband predistorter is investigated by the experimental results.

1. Introduction

To support high-rate data transmission in WLAN systems, the IEEE 802.11a standard incorporates multi-carrier modulation Orthogonal Frequency Division Multiplexing (OFDM) applying a small time interval known as a guard interval in OFDM transmissions can prevent intersymbol interference (ISI) and interchannel interference (ICI) [1]. However, the major problem of an OFDM-based system is its sensitivity to nonlinear distortion due to the large PAPR, which can be as high as 12 dB in some cases. As the large amplitude fluctuations of OFDM signals tend to reduce the power efficiency of the RF PA in a transmitter, the use of a linearizer is crucial. To design a linearizer it is necessary to have some information about the behavior of the PA's nonlinearity. The most commonly used functions to describe the power amplifier transfer characteristics are amplitude conversion (AM/AM) and phase conversion (AM/PM) functions [2]. In a wideband transmitter/HPA system such as OFDM, the nonlinear system response depends not only on the input envelope amplitude, but also on its frequency (memory effect). Generally, the memory is categorized as either electrothermal or as electrical memory effect [3]. Since the thermal filter time constant is very much larger than the inverse of the signal bandwidth in a broad-band wireless transmitter, the electrical memory effect is the dominant source of the spectrum regrowth. Therefore, the memory effect discussed in the remainder of this paper is limited to the electrical memory effect. Several different predistorter architectures, intended to compensate for the nonlinear distortion with memory effect, have been reported in the literature [4], [5]. The most common type of predistorter is that based on a two-box structure, known as either a Hammerstein or a Wiener predistorter, depending on the cascading order of the memoryless nonlinearity and linear filter [4]. In this paper, first an adaptive digital baseband compensator based on the Hammerstein system is developed to overcome the nonlinear distortion as well as memory effect in a prototype RF front-end transmitter. Next, the effectiveness of the proposed compensator is investigated by measuring the EVM and output RF spectrum (ORS) using the test bed in the experimental validation. Finally, some conclusions are drawn.

2. Identification of Hammerstein Predistorter for PA Wiener model

It is assumed the complex envelope of the input signal to the PA to be $u(t)$ as (1) in which $r(t)$ and $\theta(t)$ are its time-varying amplitude and phase respectively and the complex envelope of the PA output signal is as follows:

$$u(t) = r(t)e^{j\theta(t)} \tag{1}$$

$$y(t) = |f(r(t))|e^{j(\theta(t)+\angle f(r(t)))} \tag{2}$$

Where $f(.)$ is transfer function of PA and $|f(r(t))|$ is AM/AM and $\angle f(r(t))$ is AM/PM conversions which for a bandpass memoryless nonlinearity can be modeled by power series. However, for broadband application in which the input

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signal to the PA is a multi-carrier with time-varying envelope, nonlinearity with memory, *f(.)* is modeled by frequency-dependent complex polynomial defined as:

$$f(r(t),\omega_m) = a_1(\omega_m)r(t) + \cdots + a_{2n-1}(\omega_m)r(t)^{2n-1} = \sum_{k=1}^{K} a_{2k-1}(\omega_m)\, r(t)^{2k-1} \tag{3}$$

Where $\omega_m = 2\pi f_m = 2\pi(f_0 + m\Delta f)$ and $m = 1,2,\dots,M$ is the number of carriers. Therefore, the output of a HPA with memory effect can be written as:

$$y(t) = |f(r(t),\omega_m)| \cos(\omega_c t + \theta(t) + \angle\, f(r(t),\omega_m) \tag{4}$$

In order to derive the complex coefficients of the transfer function, $a_{2k-1}(\omega_m)$, two-tone measurement sweeping the tone spacing between two carriers is carried on. Numerical optimization procedure based on the Wiener system is used in a way the frequency dependent transfer functions in (4) are fitted to the Wiener model. First, the inverse function of memoryless nonlinearity basis on the raw measured data, as shown in Fig. 1, is used to extract the intermediate variable $v(k)$ which is required for Linear Time Invariant (LTI) filter coefficients identification as follows.

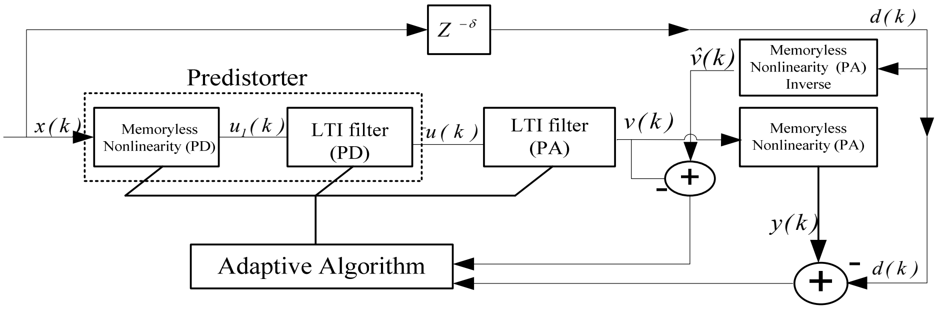


Figure 1: Adaptive structure to predict the predistorter parameters

The LTI filter in this process is assumed to be a Finite Impulse Response Filter (FIR) due to its stability. It is assumed that the output of the modeled structure for k_{th} sampled data is given by:

$$y(k) = \sum_{p=1}^{P} a_{2p-1} v(k)^{2p-1} = f\big(v(k)\big) \tag{5}$$

Where

$$v(k) = \sum_{n=0}^{N} \beta_n u(n-k) \tag{6}$$

And N and P denote the order of the FIR filter taps, and the order of the static nonlinear filter of PA respectively. The coefficients of the system estimator, a_{2p-1} and β_n, are adjusted to minimise the Mean Square Error (MSE) in the cost function of $E\{|e(k)|^2\}$ defined as:

$$e(k) = y_{meas}(k) - \sum_{p=1}^{P} a_{2p-1} (\sum_{n=0}^{N} \beta_n u(n-k))^{2p-1} \tag{7}$$

Where y_{meas} is PA output measured data. In order to solve the problem of integration of the filter coefficients in a power series, estimation of the intermediate variable $v(k)$ is performed by these assumptions: the nonlinear function (polynomials) is invertible and the linear subsystem is stable. Accordingly, to find the intermediate variable based on the (6), the inverse function of $f(\cdot)$ is estimated by polynomials of order L similar to the process described in [2]. So the adaptive algorithm to update the coefficients is defined as:

$$\hat{\beta}_n^{(k+1)} = \hat{\beta}_n^{(k)} + \mu\, \frac{\big(v(k)-\hat{v}(k)\big)\, u^*(k-n)}{\epsilon + \|u(k-n)\|^2} \tag{8}$$

Where μ represents the step-size constant of β that controls the stability and convergence speed of the algorithm and ϵ has small positive value which is used for the modification of the NLMS algorithm in case of small amount of $\|u(k)\|$. Accordingly, a Hammerstein predistorter is used for compensation of nonlinear PA in order to reduce performance degradation in a broad-band wireless transmitter based on the block diagram in Fig. 1. The predistorter is decomposed into a nonlinear static memoryless subsystem and a linear dynamic one. The static memoryless subsystem is intended to pre-compensate for the static nonlinearity of the transmitter, while the linear dynamic filter is focused on suppressing the spectrum regrowth caused by the memory effects. For predistorter parameter approximation according to the Fig. 1 $v(k)$ can be written as (9). Where M denotes the memory length of the linear inverse filter and Q denotes the order of the memoryless nonlinear filter of PD. By rewriting the $v(k)$ in a compact matrix notation, it results:

$$v(k) = \sum_{n=0}^{N} \beta_n \Big(\sum_{m=0}^{M} \lambda_m \Big(\sum_{q=1}^{Q} (\alpha_q x^q (k-m-n))\Big)\Big) \tag{9}$$

$$V_k = C_k . R_k \tag{10}$$

Where C_k and R_k are defined as follows:

$$C_k = [\beta_0\lambda_0\alpha_1, \dots, \beta_0\lambda_0\alpha_Q, \dots, \beta_0\lambda_M\alpha_1, \dots, \beta_0\lambda_M\alpha_Q, \dots\ , \beta_N\lambda_M\alpha_1, \dots, , \beta_N\lambda_M\alpha_Q\ ] \tag{11}$$

$$R_k = [x(k), \dots x^Q(k), \dots, x(k-M), \dots, x^Q(k-M), \dots, x(k-M-N), \dots, x^Q(k-M-N)]^T \tag{12}$$

For adaptive approximation of coefficients of C_k the LMS algorithm is applied and the updating equation is as follows:

$$C^{(k+1)} = C^{(k)} + \mu_c \frac{(v(k)-\hat{v}(k))^*\ R_k}{\epsilon + \|R_k\|^2} \tag{13}$$

In this process $\hat{v}(k) = f^{-1}(d(k))$ and μ_c is the step size, which influences the convergence of the algorithm. Since there is a trade-off between the convergence speed and stability, simply choosing a large value of μ_c to have a faster convergence is not feasible. For this reason, a trial and error method based on the convergence condition of the LMS algorithm were adopted. Moreover, $d(k)$ is the version of the input signal $x(k)$, delayed by the δ samples that account for causality of the predistorter.

3. Experimental Results

In order to properly measure the transmitter performance in presence of the compensator and nonlinear distortion a test setup as shown in Fig. 2 has been used.

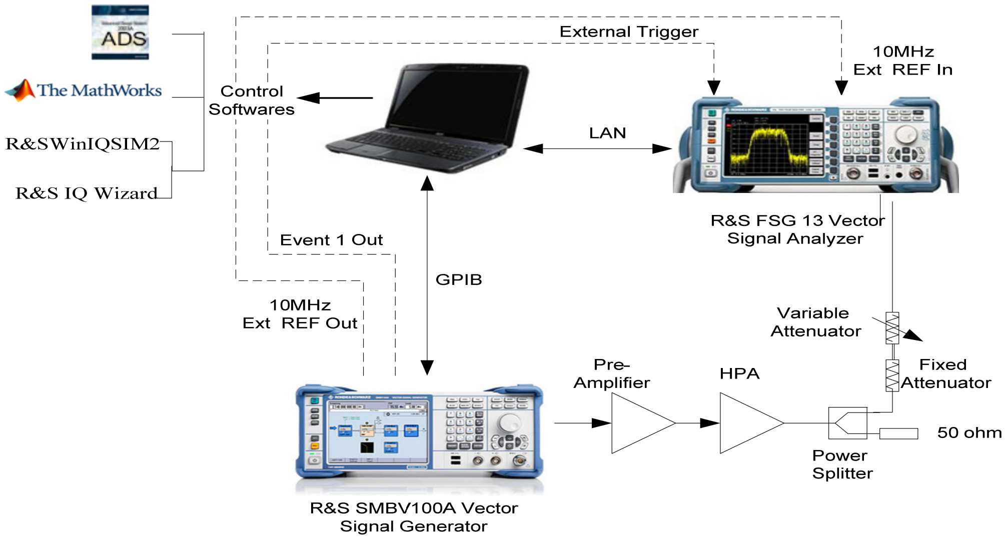
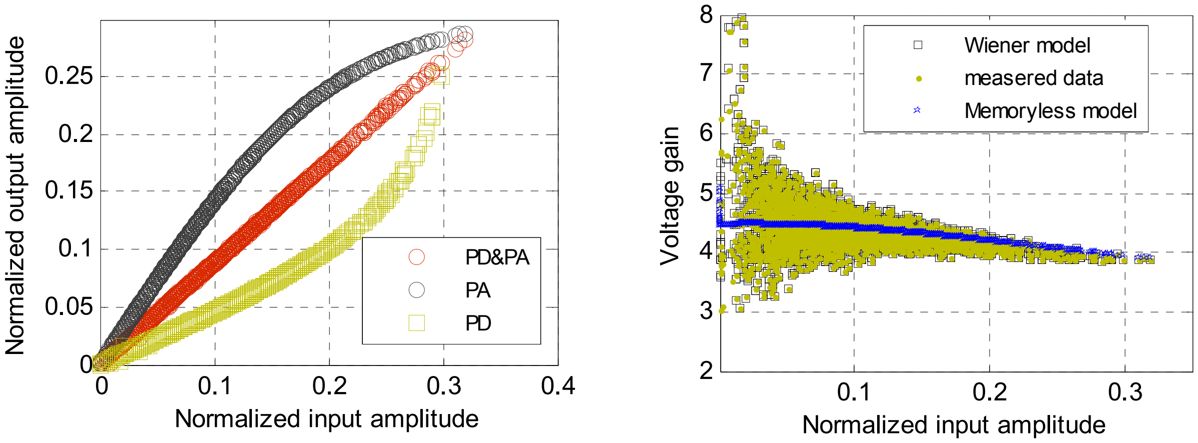


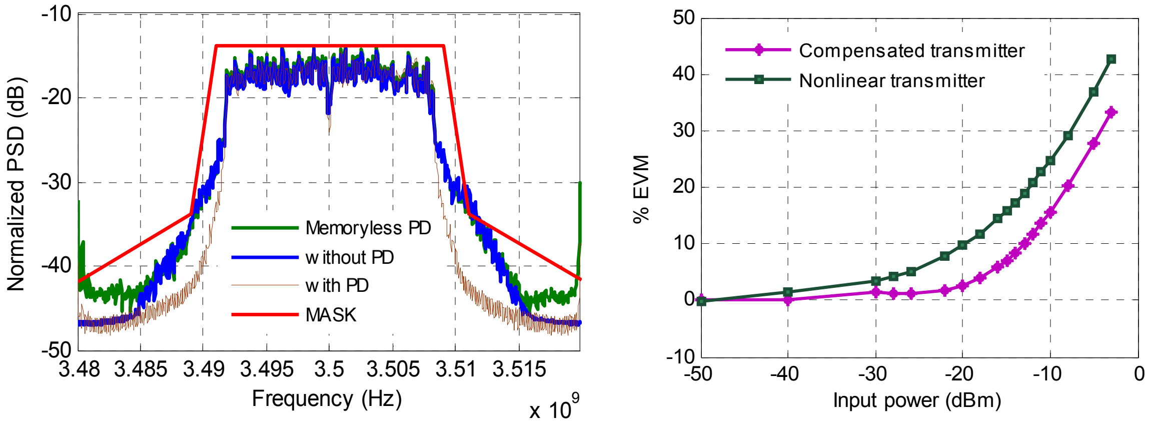
Figure 2: Predistorter experimental test setup

The test environment integrated a Rohde & Schwarz Vector Signal Generator, a Vector Signal Analyzer, a Spectrum Analyzer and accompanying software. The linearizer transmitter consists of a predistorter algorithm integrated in the R&S software and MATLAB which are installed in the local PC, plus the VSG and the HPA. I/Q vectors are turned into the R&S waveform file format to be loaded on signal generator. The predistorted data is up-converted to an RF carrier based on the IEEE 802.11a standard with 54 Mbps sample rate and 64-QAM OFDM signals in the VSG to be fed to the HPA. The receiver physically consists of the R&S Vector Signal Analyzer. The accuracy of prediction of PD and PA models for the output spectrum response of wideband systems with memory effects is shown in Fig. 3(a) and 3(b), respectively. Comparing to the memoryless model derived from single tone measurements it can be observed that the inclusion of memory effects afforded by the proposed method dramatically improved the output response. Fig. 4 (a) and (b) illustrate the effectiveness of the compensator in terms of the improvement in EVM values and ACPR as the PA can perform acceptably according to the IEEE standard with just 4 dB back-off.



(a) (b)

Figure 3: (a) PD and PA transfer functions (b) PA Gain



(a) (b)

Figure 4: (a) Output power spectrum and (b) EVM performance at 4 dB back-off

4. Conclusion

In order to model a PA, taking into account the memory effects, the Wiener-based structure was proposed and used. It was observed that the inclusion of memory effects afforded by the proposed method dramatically improved the output response. Consequently, to overcome the influence of nonlinear distortion on the OFDM signal, an adaptive Hammerstein predistorter was also proposed which showed the ACPR improvement up to 13dB with higher convergence speed compared to the previous work in [4].

5. References

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