DIGITAL PREDISTORTION BASED ON ENVELOPE FEEDBACK

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ABSTRACT

A new digital predistortion (DPD) technique based on envelope feedback is proposed for linearization of power amplifiers (PAs). Unlike conventional DPD techniques that need frequency down converters (FDCs) in the feedback path to recover the complex envelope of the PA output, the proposed technique does not need an FDC. Instead it employs two envelope detectors, estimating the envelope of the PA output and that of the difference signal between the PA input and the PA output. It is shown that the complex envelope of the PA output can be estimated from the two envelope feedbacks if the sign of the phase distortion of the AM-PM characteristic remains the same for all PA input magnitudes. Simulation results show that the performance of the proposed DPD is comparable to the conventional DPD employing an FDC.

Index Terms— Envelope feedback, indirect learning, polynomial, power amplifier(PA), predistortion

1. INTRODUCTION

A power amplifier (PA) is an indispensable component to transmit signals to a remote destination in wireless communications. To ensure good signal quality at the PA output, linear PAs are required. However, PAs are generally nonlinear devices causing problems such as spectral regrowth (or spectral broadening) and inband signal distortion: the former increases inter-channel interference and the latter degrades signal quality often measured by the error vector magnitude (EVM) [1]. To overcome these difficulties caused by the nonlinearity, many linearization techniques have been proposed, including analog/digital predistortion, feedforward, and feedback methods [2]. Among them, DPD has been recognized as a powerful tool that can exhibit excellent linearization characteristics. However, use of DPD is limited because of its complexity in implementation: DPD needs an FDC in the feedback path, which is not simple to implement, to recover the complex envelope of the PA output. The objective of this paper is to develope a DPD technique that does not require an FDC.

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The proposed DPD employs two envelope detectors instead of an FDC; they detect the envelope of the PA output and that of the difference signal between the PA input and output. It is shown that the complex envelope of the PA output can be estimated using the two envelopes if the sign of the phase difference between PA's input and output signals, which is the phase distortion given by the AM-PM characteristic curve, remains the same for all magnitude values of the PA input. This condition on the sign of the phase distortion, which will be referred to as the $phase\ sign\ condition$, is satisfied by many practical PAs [3], [4]. Simulation results show that the performance of the proposed DPD is comparable to the conventional DPD employing an FDC. Since the envelope detectors are considerably simpler to implement than an FDC, the proposed DPD is a useful alternative to the conventional DPD when the PA meets the phase sign condition.

The organization of this paper is as follows. Section 2 describes a transmitter model employing the proposed envelope feedback. The proposed DPD is developed in Section 3. Section 4 and Section 5 presents the simulation results and conclusion, respectively.

2. DPD STRUCTURE AND SIGNAL MODEL

Fig. 1 compares the proposed DPD structure with the conventional one. The two structures are essentially the same with the exception that the former employs two envelope detectors in the feedback path while the latter employs an FDC. The envelope detectors of the proposed scheme estimate the envelope of the PA output (feedback 2 in Fig. 1(b)) and that of the difference signal between PA input and the PA output (feedback 1 in Fig. 1(b)). Using these two feedback information, we extract exact amplitude and phase information of PA output as described in the next section. To derive the equivalent model of the transmitter in Fig. 1(b), we consider the memoryless power series PA model [2]. For simplicity, third order model is considered but extension to higher order PA is straightforward. Let $y(t)$ and $a(t)$ be the input and output of the PA, respectively, and $G(\cdot)$ denote the PA's nonlinear characteristic, then the PA output can be written as follows:

$$a(t) = G(y(t)) = BPF\{\alpha_1 y(t) + \alpha_2 y^2(t) + \alpha_3 y^3(t)\}, \quad (1)$$

where $\{\alpha_i\}$ are real coefficients characterizing the PA and $BPF\{\cdot\}$ denotes bandpass filtering around the carrier frequency ω_c. Substituting $y(t) = \mathrm{Re}\{y_b(t)e^{j\omega_c t}\}$ (where subscript 'b' means the baseband signal) in (1), we can see that the nonlinearity of PA causes nonlinear distortion at fundamental frequency ω_c and generates harmonic signals at DC, $2\omega_c$, and $3\omega_c$. By bandpass filtering, harmonics are filtered out and the PA output can be written as

$$a(t) = \mathrm{Re}\left\{a_b(t)e^{j\omega_c t}\right\}, \quad (2)$$

where $a_b(t)$ is the baseband equivalent PA output given by $a_b(t) \triangleq G_b(y_b(t)) = (w_1 + w_2|y_b(t)|^2)y_b(t)$. $G_b(\cdot)$ is the baseband equivalent PA characteristic function and $w_1 = \alpha_1$, $w_2 = \frac{3\alpha_3}{2^2}$. In general, the coefficients $\{w_i\}$ characterizing the PA are complex values since real PA have some delay elements in (1). For mathematical modeling of envelope detector, either the square-law envelope detector or the envelope detector using the Hilbert transform can be used [5]. In this paper, we consider the square-law envelope detector which is represented as $\sqrt{LPF\{2 \times (\cdot)^2\}}$ (here $LPF\{\cdot\}$ means low pass filtering). Then, the feedback signal at the first path is written as

$$f_1(t) = |y_b(t) - a_b(t)/K|, \quad (3)$$

where K is the attenuation factor. Similarly, the envelope signal at the second path is

$$f_2(t) = |a_b(t)/K|. \quad (4)$$

From (2)–(4), the baseband equivalent transmitter model can be represented as Fig. 2.

3. DESIGN OF PROPOSED DPD

In this section, we first show that the PA output signal $a_b(n)/K$ can be estimated from the two envelop signals. Then the proposed DPD algorithm based on the estimated PA output signal is derived. Specifically, a polynomial-based DPD with indirect learning algorithm is developed.

3.1. PA Output Estimation

Referring to Fig. 2, our objective is to obtain $a_b(n) = |a_b(n)|e^{j\angle(a_b(n))}$ from the two envelope signals. Since $|a_b(n)|$ can be obtained directly from the second feedback path, we need to estimate the phase of $a_b(n)$. Note that the signals that we have are $|a_b(n)/K|$, $|y_b(n) - a_b(n)/K|$, and $y_b(n)$. Fig. 3 shows the relationship among $a_b(n)/K, y_b(n)$,

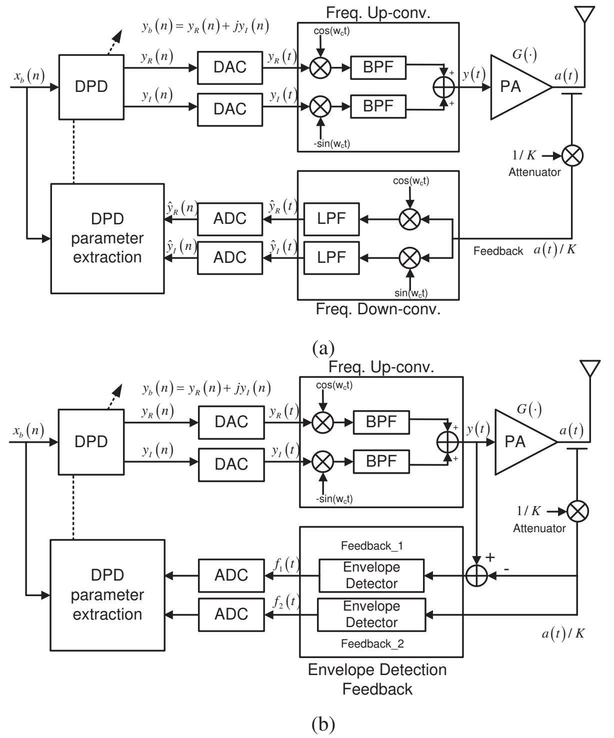

Fig. 1. (a) A conventional transmitter model employing DPD using an FDC in feedback path. (b) Proposed DPD structure using envelope detection in feedback path.

and $y_b(n) - a_b(n)/K$ in complex domain. Define $\theta \triangleq \angle(a_b(n)) - \angle(y_b(n))$. Then, $|\theta|$ can be obtained (Fig. 3) as

$$|\theta| = \cos^{-1}\left(\frac{|y_b(n)|^2 + |\frac{a_b(n)}{K}|^2 - |y_b(n) - \frac{a_b(n)}{K}|^2}{2|y_b(n)||\frac{a_b(n)}{K}|}\right). \quad (5)$$

Thus, the absolute phase difference between the PA input and the PA output can be obtained. If the sign of the phase difference θ remains the same for all PA input magnitude $|y_b(n)|$ (i.e., the phase sign condition is met) and the sign is known a priori, then θ can be obtained from (5) and the PA output is given by

$$a_b(n) = |a_b(n)|e^{j(\angle(y_b(n))+\theta)}. \quad (6)$$

The phase sign condition is met for typical TWTA PAs but the condtion is not always satisfied for LDMOS PAs [4].

3.2. PD Algorithm

Given the PA output estimate, the proposed DPD is developed following the steps for designing conventional DPD [6]– [8]. In this paper, a polynomial-based DPD is employed and its parameters are estimated by indirect learning methods. Extending the baseband model in (2) to a higher order case, PA

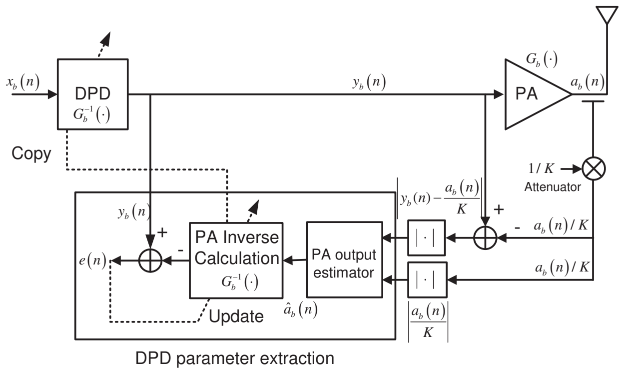

Fig. 2. Baseband equivalent transmitter model employing envelope detectors.

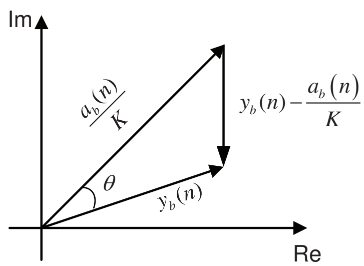

Fig. 3. Input and output signals in complex domain.

can be modeled as

$$a_b(n) = G_b(y_b(n)) = \sum_{k=1}^{P} w_k^* |y_b(n)|^{2(k-1)} y_b(n) = \mathbf{w}^H \mathbf{y}(n), \tag{7}$$

where $(2P-1)$ is the maximum nonlinear order, $\mathbf{w}$ is the coefficient vector of the PA model defined by $\mathbf{w} = [w_1, w_2, \cdots, w_P]^T$, and $\mathbf{y}(n) = [y_b(n), y_b(n)|y_b(n)|^2, \cdots, y_b(n)|y_b(n)|^{2(P-1)}]^T$. Since it is difficult to find the exact inverse of the nonlinear model in (7), an approximated polynomial model is used for the DPD function. The DPD, denoted by $G_b^{-1}(\cdot)$, can be written as

$$y_b(n) = G_b^{-1}(x_b(n)) = \sum_{k=1}^{Q} h_k^* |x_b(n)|^{2(k-1)} x_b(n) = \mathbf{h}^H \mathbf{x}(n), \tag{8}$$

where $x_b(n)$ is the DPD input; $(2Q-1)$ is the order of the DPD; $\{h_k\}$ is the DPD coefficients that satisfy $G_b(G_b^{-1}(x_b(n))) \approx x_b(n)$; $\mathbf{h} = [h_1, h_2, \cdots, h_Q]^T$; and $\mathbf{x}(n) = [x_b(n), x_b(n)|x_b(n)|^2, \cdots, x_b(n)|x_b(n)|^{2(Q-1)}]^T$. Since the characteristics of the PA can be changed over time and temperature, the DPD parameters are adaptively updated based on indirect learning method [8]. In this method, a post distorter in the feedback path is updated, and the parameters of the post distorter are copied to the DPD in the feedforward path as shown in Fig. 2.

To find the post distortion parameters, we define the following mean square error cost function

$$\mathcal{E} = E[|e(n)|^2], \tag{9}$$

where $E[\cdot]$ is the expectation operator and $e(n) = y_b(n) - G_b^{-1}(\frac{a_b(n)}{K})$. For $a_b(n)$, the estimated output signal in (6) is used. Then, the error $e(n)$ can be written as

$$e(n) = y_b(n) - \mathbf{h}^H \mathbf{a}(n), \tag{10}$$

where $\mathbf{a}(n) = [\frac{a_b(n)}{K}, \frac{a_b(n)}{K}|\frac{a_b(n)}{K}|^2, \cdots, \frac{a_b(n)}{K}|\frac{a_b(n)}{K}|^{2(Q-1)}]^T$. Using (10), the adaptive algorithm that minimizes (9) can be derived as follows [9]:

$$\begin{aligned} \mathbf{h}(n+1) =& \mathbf{h}(n) - \frac{1}{2}\mu D \frac{\partial \mathcal{E}}{\partial \mathbf{h}^*} \\ =& \mathbf{h}(n) + \mu D e^*(n) \mathbf{a}(n), \end{aligned} \tag{11}$$

where μ is the step size and D is a diagonal matrix for accelerating the convergence. After the convergence, the parameters $\mathbf{h}$ are copied to the PD in the feedforward path.

4. SIMULATION RESULTS

The performance of the proposed DPD technique is demonstrated through a computer simulation. Simulation environments are as follows. Transmitted symbols are modulated by 16 quadrature amplitude modulation (16-QAM) and pulse-shaped by a square root raised cosine filter with roll-off factor 0.22. The operating (sampling) rate of the pulse shaping filter (PSF) is 10 times oversampled with respect to the symbol rate. The output of PSF is predistorted by the DPD. To model an analog up/down-converter, an analog RF PA, and an envelope detector, we interpolate the PD output by a factor of 30. The carrier frequency is $\omega_c = 2\pi \times 10F_s$ where F_s is the symbol rate. We assume that K is equal to 1. The RF PA is modeled by a 5-th order nonlinear model with some delay elements [2]:

$$a(n) = BPF\left\{\sum_{i=1}^{3}\sum_{k=1}^{5} w_{i,k} y^k (n-\tau_i)\right\}. \tag{12}$$

where $w_{1,1} = 1.5, w_{1,2} = -0.5, w_{1,3} = -0.5, w_{1,4} = 1.25, w_{1,5} = -0.75$, $w_{2,1} = -0.1, w_{2,2} = 0.1, w_{2,3} = 0.1, w_{2,4} = -0.05, w_{2,5} = -0.05$, $w_{3,1} = 0.05, w_{3,2} = -0.2, w_{3,3} = -0.2, w_{3,4} = 0.05, w_{3,5} = 0.05$, and $\tau_1 = 0, \tau_2 = 1, \tau_3 = 2$. Fig. 4 shows AM-AM and AM-PM characteristics of the RF PA model in (12). For modeling the envelope detector, finite impulse response (FIR)-type low pass filter is implemented. The initial value of the LMS algorithm in (11) is: $\mathbf{h} = [1, 0, \cdots, 0]^T$. The scaled diagonal matrix μD in (11) is given by $\mu D = diag[0.1, 1, 2, 5]$.

Fig. 6 shows the learning curves for the mean square errors (MSE), which are obtained by averaging over 100 trials.

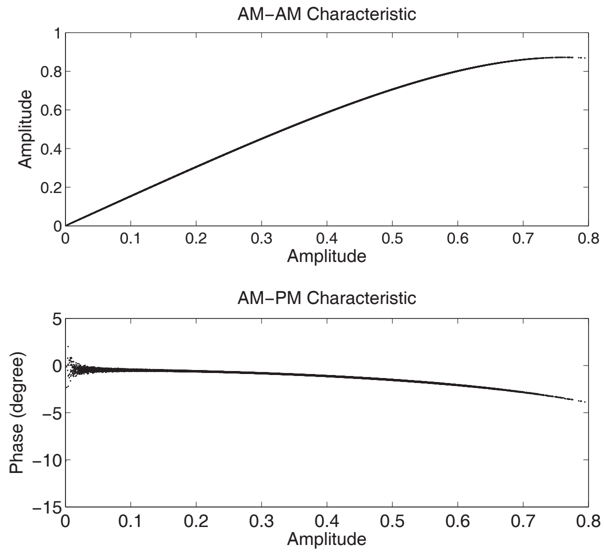

Fig. 4. PA characteristic curves.

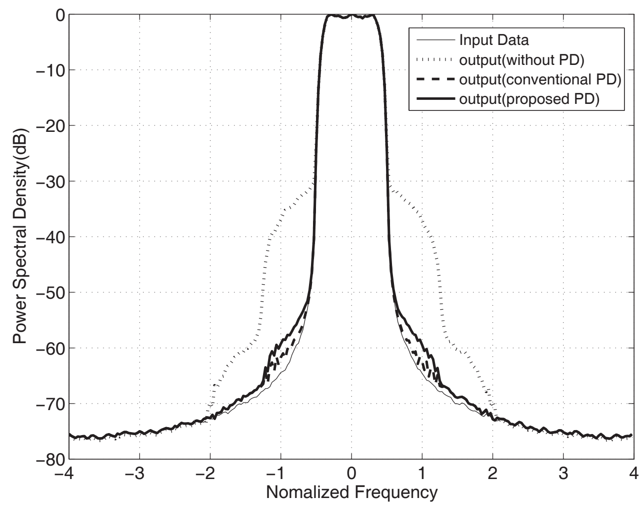

Fig. 5. Comparison of PSD performance

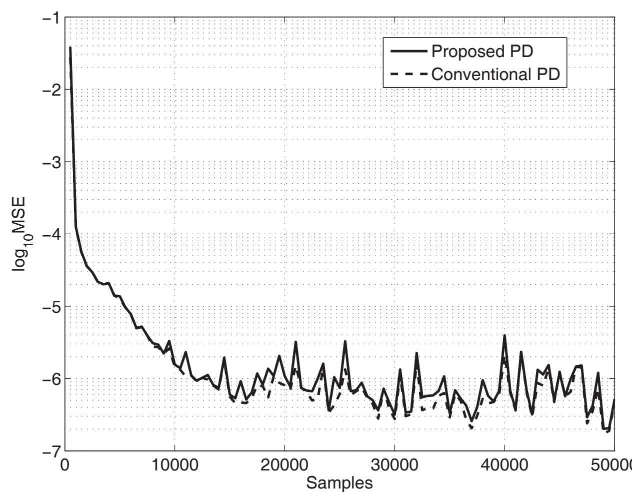

Fig. 6. Learning Curves.

The proposed and conventional DPD exhibit almost identical convergence characteristics. Fig. 5 demonstrates the output power spectral density (PSD) performances. The results show that the proposed PD can effectively linearize the nonlinear PA and the linearization performance is comparable to the conventional method with full feedback.

5. CONCLUSION

A predistortion technique based on two envelope feedback signals was proposed. Under the condition that the sign of the phase distortion of the AM-PM characteristic remains the same for all PA input magnitude, we showed that the complex envelope of the PA output can be estimated using the two envelope feedback signals. The proposed DPD is considerably simpler to implement than the conventional DPD, yet performance of the former is comparable to that of the latter.

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