

# A low cost adaptive digital predistorter for linearization of power amplifiers in MIMO transmitters

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**Abstract:** An adaptive digital predistortion (PD) technique is proposed for linearization of power amplifiers (PAs) in multiple-input multiple-output (MIMO) transmitters. We consider a PD structure equipped with only one combined feedback path while conventional systems have multiple feedback paths. Hence, the proposed structure is much simpler than that of multiple feedback paths. Based on the structure, a new PD algorithm is derived. The simulation results show that linearization performance of the proposed method is almost the same as the conventional multiple feedback technique while the former is much simpler to implement than the latter.

**Keywords:** predistortion, MIMO, polynomial, power amplifier

**Classification:** Wireless communication hardware

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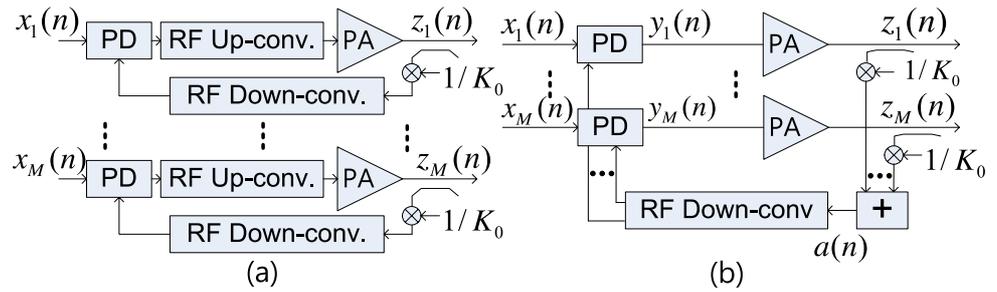
## 1 Introduction

Multiple input multiple output (MIMO) techniques are attractive and promising ones to solve problems such as signal attenuation, interference, and spectrum limitation in wireless communications. MIMO can increase data rates and/or coverage of service area, and improve signal reliability while consuming no additional radio frequencies. To improve spectral efficiency and reliability, current wireless standards such as IEEE 802.11 and 802.16 use MIMO technology.

On the transmitter side of  $M \times N$  MIMO systems, there are  $M$  independent transmit radio frequency (RF) paths including power amplifiers (PAs). Typically, PAs have nonlinear characteristics and cause two major problems: One is spectral regrowth and the other is inband signal distortion. The former can increase the inter-channel interference and the latter can degrade the transmit signal quality which can be measured as error vector magnitude (EVM). One simple remedy to mitigate this impact is to back-off the PA output from the saturation power to operate in its linear region. However, since current modulation techniques such as CDMA (code division multiple access) or OFDM (orthogonal frequency division multiplexing) tend to have high peak-to-average power ratio (PAPR), the back-off technique requires large back-off from the saturation level, which leads to low power efficiency of the PA. To compensate for the nonlinearity of the PAs and increase the efficiency, many techniques have been proposed such as digital PD, feedforward, and feedback methods [1]. Among them, the digital PD is a popular technique. The digital PD techniques utilize a predistorter in the baseband domain, whose characteristic is inverse of the PA to compensate for the nonlinearity [2, 3, 4].

When applying the digital PD technique in  $M$  multiple transmit antenna systems,  $M$  PD blocks and  $M$  feedback paths are needed as shown in Fig. 1(a). However, multiple feedback paths increase cost and size of the transmitter. To reduce the feedback overhead, the  $M$  PA outputs are combined together and feedback to the PD algorithm block from only one feedback path in the proposed method. From the combined feedback signal, we jointly find the  $M$  PA characteristics. After PA identification, the PD parameters are obtained based on the steepest descent algorithm. Simulation results show that the proposed method achieves almost the same convergence time and linearization performance compared with the conventional multiple feedback system while the former is much simpler to implement than the latter.

The organization of this paper is as follows. Section II describes the proposed MIMO transmitter model with PD block. The proposed PD algorithm is developed in Section III. Section IV shows the simulation results and Section V concludes the paper.



**Fig. 1.** DPD system model for multiple transmitter antennas. (a) Multiple feedback. (b) Proposed feedback.

## 2 Proposed MIMO transmitter with predistortion

Fig. 1 (b) shows the proposed transmitter model with digital predistortion. Since PAs have different nonlinear characteristics, denoted by  $\varphi_j(\cdot)$  for  $j = 1, \dots, M$ , multiple predistorters are needed at each input of the PAs to compensate for the nonlinearity of the corresponding PAs. Assuming that PAs have memoryless characteristics<sup>1</sup>, the PAs can be represented as follows:

$$z_m(n) = \varphi_m(y_m(n)) = \sum_{k=1}^L w_{k,m}^* |y_m(n)|^{2(k-1)} y_m(n) = \mathbf{w}_m^H \mathbf{y}_m(n), \quad (1)$$

where  $2L - 1$  is the maximum nonlinear polynomial order,  $\mathbf{w}_m = [\hat{w}_{1,m}, \hat{w}_{2,m}, \dots, \hat{w}_{L,m}]^T$ ,  $\{w_{k,m}\}$  are the characteristic coefficients of the  $m$ -th PA, and  $\mathbf{y}_m(n) = [y_m(n), y_m(n)|y_m(n)|^2, \dots, y_m(n)|y_m(n)|^{2(L-1)}]^T$ .

Since it is difficult to find the exact inverse of the nonlinear model in (1), an approximated polynomial model is used for the inverse function in practice. The inverse can be written as follows:

$$y_m(n) = \varphi_m^{-1}(x_m(n)) = \sum_{k=1}^Q h_{k,m}^* |x_m(n)|^{2(k-1)} x_m(n) = \mathbf{h}_m^H \mathbf{x}_m(n). \quad (2)$$

where  $2Q - 1$  is the nonlinear order,  $\{h_{k,m}\}$  is the coefficients of the  $m$ -th PD that satisfy  $\varphi_m(\varphi_m^{-1}(x_m(n))) \approx K_o x_m(n)$ ,  $\mathbf{h}_m = [h_{1,m}, h_{2,m}, \dots, h_{Q,m}]^T$ , and  $\mathbf{x}_m(n) = [x_m(n), x_m(n)|x_m(n)|^2, \dots, x_m(n)|x_m(n)|^{2(Q-1)}]^T$ . Since the characteristics of the PA can be changing over time and temperature, the parameters of PDs should be adaptively updated. To find the parameters of the PD,  $M$  PA output signals are required. Hence,  $M$  separate feedback paths are needed. These multiple feedback paths may increase cost and size of MIMO transmitters since each feedback path requires down-conversion to baseband and an analog-to-digital converter (ADC) and so on. To simplify the MIMO transmitter, we suggest to combine all the  $M$  PA outputs and construct one feedback path using the combined signal. Consequently, the proposed MIMO transmitter structure requires only one downconverter and one ADC. In the next section, we develop the PD algorithm based on the combined feedback signal.

<sup>1</sup>For PAs with memory effects, a memory polynomial model [3] can be used.

### 3 Development of the proposed algorithm

The proposed algorithm consists of two steps. The first step is PA identification and the second step is PD parameter calculation from the identified PA characteristic.

#### 3.1 PA identification

We assume that independent data stream is transmitted at each path. From (1), the sum of PA outputs in the feedback path can be modeled as follows:

$$\begin{aligned} a(n) &= \frac{z_1(n)}{K_o} + \frac{z_2(n)}{K_o} + \dots + \frac{z_M(n)}{K_o}, \\ \hat{a}(n) &= \frac{1}{K_o} \mathbf{w}^H \mathbf{y}(n) \end{aligned} \quad (3)$$

where  $\mathbf{w} = [\mathbf{w}_1^T, \mathbf{w}_2^T, \dots, \mathbf{w}_M^T]^T$ ,  $\mathbf{y}(n) = [\mathbf{y}_1^T(n), \mathbf{y}_2^T(n), \dots, \mathbf{y}_M^T(n)]^T$ , and  $K_o$  is the gain of the PA. (3) implies that the feedback signal is the attenuated PA output by  $1/K_o$ . To find the characteristics of the PAs, we define a cost function as follows:

$$\mathcal{E}_{\mathbf{w}} = E[|e(n)|^2] \quad (4)$$

where  $E[\cdot]$  is an expectation operator and  $e(n) = a(n) - \hat{a}(n)$ . An adaptive algorithm for updating  $\mathbf{w}$  that minimizes the cost function can be obtained by the diagonally scaled steepest descent method [7]:

$$\hat{\mathbf{w}}(n+1) = \hat{\mathbf{w}}(n) + \mu \mathbf{D} e^*(n) \mathbf{y}(n) \quad (5)$$

where  $\mu$  is a step size and  $\mathbf{D}$  is a diagonally scaling matrix which improves convergence characteristic of the update algorithm. The diagonal scaling matrix is considered because the elements of  $\mathbf{y}(n)$  have different nonlinear orders. After convergence, the  $M$  PA characteristics can be obtained because  $\mathbf{w}$  is composed of  $\mathbf{w}_1, \dots, \mathbf{w}_M$ .

#### 3.2 PD calculation

The parameters of the  $M$  PDs can be calculated independently since we have separate  $M$  PA characteristics. To find the PD parameters, we define a cost function for the  $m$ -th PA as follows:

$$\mathcal{E}_{\mathbf{h}_m} = E[|e_{\mathbf{h}_m}(n)|^2] \quad (6)$$

where  $e_{\mathbf{h}_m}(n) = x_m(n) - z_m(n)/K_o$ . Since there is only one combined feedback path,  $z_m(n)$  can not be used directly. Alternatively, we estimate the signal using the estimated PA characteristics. Thus,  $z_m(n)$  can be estimated as follows:

$$\hat{z}_m(n) = \hat{\mathbf{w}}_m^H \mathbf{y}_m(n). \quad (7)$$

The error signal can be rewritten as

$$e_{\mathbf{h}_m}(n) = x_m(n) - \frac{1}{K_o} \hat{\mathbf{w}}_m^H \mathbf{y}_m(n). \quad (8)$$

Using (8), the update algorithm that minimizes (6) can be obtained by the same method in Section 3.1:

$$\begin{aligned} \mathbf{h}_m(n+1) &= \mathbf{h}_m(n) - \frac{1}{2}\mu_m \mathbf{D}_m \frac{\partial \mathcal{E}_{\mathbf{h}_m}}{\partial \mathbf{h}_m^*} \\ &= \mathbf{h}_m(n) - \frac{1}{2}\mu_m \mathbf{D}_m \frac{\partial y_m(n)}{\partial \mathbf{h}_m^*} \frac{\partial \mathcal{E}_{\mathbf{h}_m}}{\partial y_m(n)} \\ &= \mathbf{h}_m(n) + 2\mu_m \mathbf{D}_m [e_{\mathbf{h}_m}^*(n)(\mathbf{w}_m^H \mathbf{v}_{1m}(n)) \mathbf{x}_m(n) \\ &\quad + e_{\mathbf{h}_m}(n)(\mathbf{w}_m^T \mathbf{v}_{2m}(n)) \mathbf{x}_m(n)], \end{aligned} \quad (9)$$

where  $\mu_m$  is a step size,  $\mathbf{v}_{1m}(n) = [1, 2|y_m(n)|^2, 3|y_m(n)|^4, \dots, L|y_m(n)|^{2(L-1)}]$ ,  $\mathbf{v}_{2m}(n) = [0, y_m^{*2}(n), 2y_m^{*2}(n)|y_m(n)|^2, \dots, (L-1)y_m^{*2}(n)|y_m(n)|^{(L-2)}]$ , and  $\mathbf{D}_m$  is a scaling diagonal matrix.

#### 4 Simulation results

The performance of the proposed PD is demonstrated through computer simulation. The simulation environments are as follows. We consider a two transmit antenna system. Two independent bit streams are generated and modulated by 16 quadrature amplitude modulation (16-QAM). The modulated signals are pulse-shaped by a square root raised cosine (RRC) filter with roll-off 0.25. The sampling clock of the pulse shaping filter (RRC) is 10 times the symbol rate. For the  $m$ -th nonlinear PA model, we consider Saleh model given by [6]

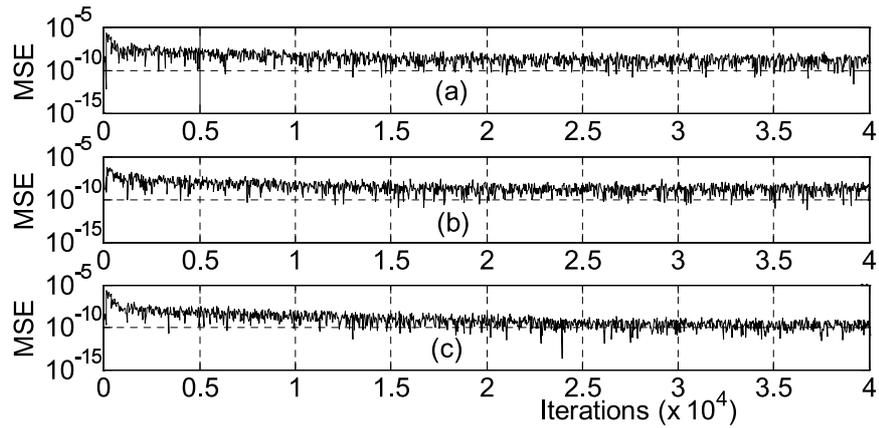
$$\varphi_m(y_m(n)) = \frac{1.1\alpha_m y_m(n)}{1 + 0.3|y_m(n)|^2} \exp\left(j \frac{0.8\beta_m |y_m(n)|^2}{1 + 3|y_m(n)|^2}\right). \quad (10)$$

where  $\alpha_m$  and  $\beta_m$  determine the PA characteristic. In the simulation, we use  $\alpha_1 = 1$  and  $\beta_1 = 1$  for Antenna 1, and  $\alpha_2 = 1.01$  and  $\beta_2 = 0.97$  for Antenna 2. The PA gain is assumed to be 1 ( $K_o = 1$ ). We consider 7th order polynomial model for the PA and PD. For PD calculation, the step size ( $\mu_j$ ) is set to 0.15 and  $\mathbf{D}_j = \text{diag}[1, 50, 500, 2000]$ .

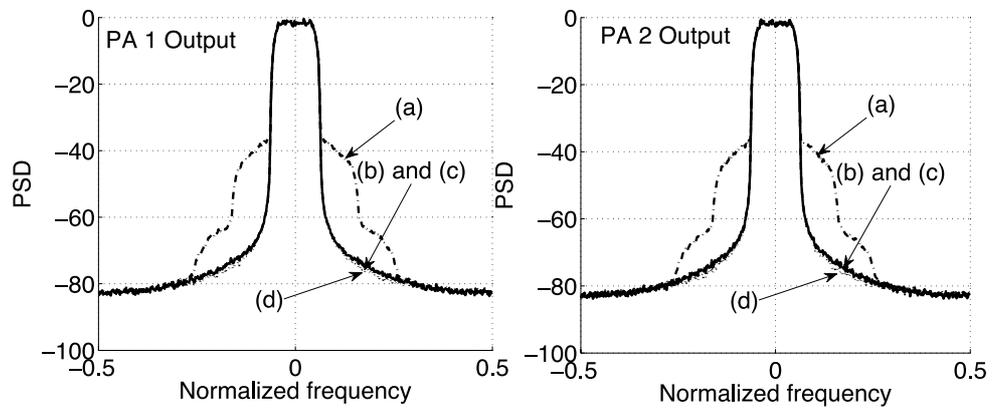
Fig. 2 shows learning curves for PD parameters. The proposed algorithm have comparable convergence speed to the multiple feedback systems. Both PD parameters for the first and second PA in the proposed method are converged in about 15,000 iterations and have the mean square value (MSE) around  $10^{-9}$  after convergence as shown in Fig. 2 (a) and (b). The conventional system converges in about 20,000 iterations and has the MSE value of  $10^{-10}$ . Fig. 3 shows the PSD performance at both PA outputs. Without PD, the output of the PAs are severely distorted by the nonlinearity of the PA. However, these distortions are effectively compensated by the proposed PD algorithm. Comparing with the system having multiple feedback paths, the proposed method shows almost the same PSD performance.

To compare inband signal quality at the PA outputs, we evaluate EVM. EVM is defined as follow:

$$EVM = \sqrt{\frac{E[|x_m(n) - z_m(n)/K_o|^2]}{E[|x_m(n)|^2]}} \times 100[\%]. \quad (11)$$



**Fig. 2.** Learning Curves (a)  $E[|e_{h_1}(n)|^2]$  in (6). (b)  $E[|e_{h_2}(n)|^2]$  in (6). (c) Learning curve for conventional multiple feedback system.



**Fig. 3.** PSD performance at the first and second PA outputs. (a) without PD. (b) Proposed PD. (c) conventional PD with multiple feedback paths. (d) PD input.

Without PD, the EVMs at PA 1 and PA2 are 9.49% and 9.00%, respectively, which means the signals are distorted severely. However, the EVM can be reduced significantly by applying the PDs. According to the EVM simulation, for the conventional multiple-feedback method, the EVMs at PA 1 and PA 2 are 0.056% and 0.061%, respectively, while those are 0.078% and 0.081%, respectively, for the proposed method. Although the proposed method is slightly worse than the conventional method, we can conclude that both PD techniques can significantly improve the EVM performance. Those results indicate that the proposed PD, based on the single combined feedback, can successfully linearize the PAs in MIMO systems.