Design of Digital Predistorters for Multi-Band Signals

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***Abstract*— A new digital predistortion (DPD) technique for multi-band signals is proposed. The transmitter considered in this paper has multi-band signals, and those signals are combined and amplified by a single wideband power amplifier (PA). In this case, the PA output is distorted by the nonlinear cross-products between different-band signals as well as their own nonlinear self-products. To linearize the PA and remove those nonlinear products, we propose a PD structure, which has multiple predistorters (one predistorter (PD) for one band). Each PD removes the nonlinear cross-products and self-products to mitigate the spectral regrowth for the corresponding band. Since the PD parameters for different bands are linked together, it is difficult to find the PD parameters separately. As an alternative method, we propose an iterative method for finding the PD parameters. The simulation results show that the iterative method converges well, and the proposed PD can effectively linearize the PA and remove spectral regrowth at each signal band.**

***Index Terms*—Multi-band, predistortion, power amplifier (PA), wideband**

I. Introduction

Mobile wireless communication systems have been evolved rapidly and new wireless services are emerging. Those new wireless services coexist with the old ones now. In addition, other kinds of services such as wireless local area network (WLAN) or wireless personal area network (WPAN) services are equipped in a single handset, together with the existing mobile wireless systems. To implement those multi-band/multi-mode systems, multiple radios are installed in general as shown in Fig. 1 (one radio for one band) [1]-[2]. Therefore, the same number of power amplifiers (PAs) and antennas as the number of the served bands are required, which makes the system bulky and inefficient.

In this paper, we consider the digital predistortion (PD) problem when a single wideband PA is used to amplify multi-band signals. In this transmitter model, the multi-band signals are combined and amplified by a wideband PA. Compared to the single-band transmitter, multi-band signals at the PA output are more severely distorted by nonlinear cross products between different bands as well as the nonlinear self-products

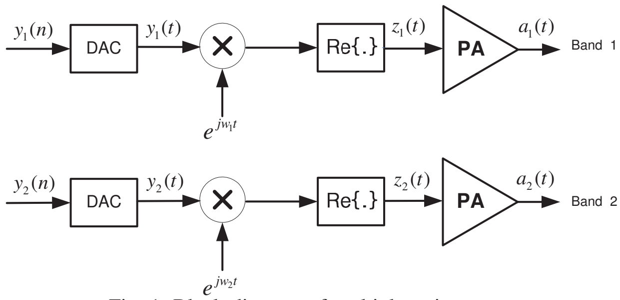

Fig. 1. Block diagram of multiple ratio system.

of each band's own signal. Those nonlinear distortions can not be compensated by conventional PD methods [3]-[6] since they do not consider the nonlinear cross products between different bands. To combat those nonlinear products and linearize the PA, we propose a new PD structure which has multiple PDs (one PD for one band). In the structure, due to the nonlinear cross-products by the PA, the PD parameters are also dependent of each other. In other words, a change in a PD parameter for a certain band affects the other PD parameters. Therefore, the PD parameters for the multiple PDs should be jointly optimized, but not separately optimized. To find the PD parameters, we propose an iterative method based on the least mean squares (LMS) criterion where the PD parameter at each band is repeatedly and sequentially updated by fixing the other PD parameters. Simulation results demonstrate that the algorithm converges as the number of iteration increases and the spectral regrowth at the PA output is significantly reduced by the proposed method.

The organization fo this paper is as follows. Section II describes the system model considered in this paper. The proposed PD structure and algorithm are described in Section III. Section IV shows the simulation results and Section V concludes the paper.

II. Multi-Band Transmitter Model

In this section, we describe the system model for multi-band transmitters. Fig. 2 shows the block diagram of the proposed system. We assume that two streams are transmitted

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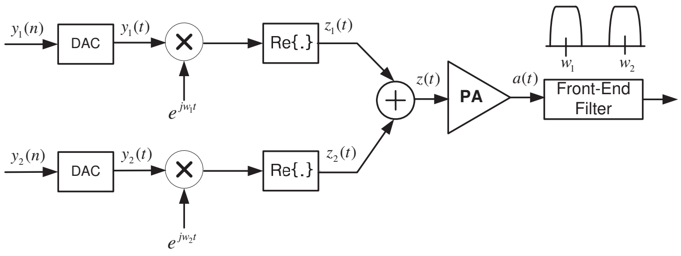

Fig. 2. Block diagram of proposed transmitter model.

using two different bands, respectively.[1] The baseband digital signals, $y_1(n)$ and $y_2(n)$, are converted into analog signals by a digital-to-analog converter (DAC) and upconverted into different frequency bands: ω_1 and ω_2, respectively. These upconveted signals are combined together and amplified by a PA. Assuming that the PA is modeled by a 3-rd order polynomial, the PA output in Fig. 2 can be represented as

$$a(t) = \alpha_1 z(t) + \alpha_2 z^2(t) + \alpha_3 z^3(t), \tag{1}$$

where $\{\alpha_i\}$ are real constants characterizing the PA. In (1), $\alpha_1 z(t)$ represents the linear component while $\alpha_2 z^2(t)$ and $\alpha_3 z^3(t)$ are the second and third nonlinear components, respectively. Substituting $z(t) = \mathrm{Re}\{y_1(t)e^{j\omega_1 t}\} + \mathrm{Re}\{y_2(t)e^{j\omega_2 t}\}$ in (1) and arranging yield

$$\begin{aligned} a(t) =& \frac{\alpha_2}{2}\left(|y_1(t)|^2 + |y_2(t)|^2\right) \\ &+ \mathrm{Re}\left\{\left(\alpha_1 y_1(t) + \frac{\alpha_3}{2^2}\left(3y_1(t)|y_1^2(t)|\right.\right.\right. \\ &\left.\left.\left. +6y_1(t)|y_2(t)|^2\right)\right) e^{j\omega_1 t}\right\} \\ &+ \mathrm{Re}\left\{\frac{\alpha_2}{2} y_1^2(t) e^{j2\omega_1 t}\right\} + \mathrm{Re}\left\{\frac{\alpha_2}{2^2} y_1^3(t) e^{j3\omega_1 t}\right\} \\ &+ \mathrm{Re}\left\{\left(\alpha_1 y_2(t) + \frac{\alpha_3}{2^2}\left(3y_2(t)|y_2^2(t)|\right.\right.\right. \\ &\left.\left.\left. +6y_2(t)|y_2(t)|^2\right)\right) e^{j\omega_2 t}\right\} \\ &+ \mathrm{Re}\left\{\frac{\alpha_2}{2} y_2^2(t) e^{j2\omega_2 t}\right\} + \mathrm{Re}\left\{\frac{\alpha_2}{2^2} y_2^3(t) e^{j3\omega_2 t}\right\} \\ &+ \cdots . \end{aligned}$$

In general, the PA output can be expressed as

$$a(t) = \sum_{k=-K}^{K} \sum_{l=-L}^{L} \mathrm{Re}\left\{G_{k,l}(y_1(t), y_2(t)) e^{j(k\omega_1 + l\omega_k)t}\right\}$$

where $G_{k,l}(y_1(t), y_2(t))$ is a nonlinear function of $y_1(t)$ and $y_2(t)$, the value $K + L$ is less than the order of (1), and k and l are the combinations that satisfy $k\omega_1 + l\omega_2 \geq 0$. For the example of the above third order nonlinear PA model, $\{G_{k,l}(y_1(t), y_2(t))\}$ are summarized in Table I. Assuming that the transmitter has a front-end bandpass filter centered at ω_1 and ω_2, as shown in Fig. 2, we need to consider the only two terms, $G_{1,0}(\cdot)$ and $G_{0,1}(\cdot)$. Denote $G_{1,0}(\cdot)$ and $G_{0,1}(\cdot)$ as $G_1(\cdot)$ and $G_2(\cdot)$, respectively for simplicity. The objective of this paper is to develop a predistortion structure and algorithm that linearizes both bands simultaneously.

[1]This paper deals with only 2 bands signals for simplicity. Extension to more than 2 bands signals is straightforward, but cumbersome.

TABLE I
$G_{k,l}(y_1(t), y_2(t))$ FOR THIRD ORDER NONLINEAR PA MODEL
($K + L = 3$ AND $\omega_2 \geq \omega_1$).

Function, Frequency	Expression
$G_{0,0}(\cdot), DC$	$\frac{\alpha_2}{2^2}\left(2\|y_1\|^2 + 2\|y_2\|^2\right)$
$G_{1,0}(\cdot), \omega_1$	$\frac{\alpha_1}{2} y_1 + \frac{\alpha_3}{2^3}\left(3y_1\|y_1\|^2 + 6y_1\|y_2\|^2\right)$
$G_{2,0}(\cdot), 2\omega_1$	$\frac{\alpha_2}{2^2} y_1^2$
$G_{3,0}(\cdot), 3\omega_1$	$\frac{\alpha_3}{2^3} y_1^3$
$G_{0,1}(\cdot), \omega_2$	$\frac{\alpha_1}{2} y_2 + \frac{\alpha_3}{2^3}\left(3y_2\|y_2\|^2 + 6y_2\|y_1\|^2\right)$
$G_{0,2}(\cdot), 2\omega_2$	$\frac{\alpha_2}{2^2} y_2^2$
$G_{0,3}(\cdot), 3\omega_2$	$\frac{\alpha_3}{2^3} y_2^3$
$G_{1,1}(\cdot), \omega_1 + \omega_2$	$\frac{\alpha_2}{2^2} 2y_1 y_2$
$G_{-1,1}(\cdot), -\omega_1 + \omega_2$	$\frac{\alpha_2}{2^2} 2y_1^* y_2$
$G_{2,1}(\cdot), 2\omega_1 + \omega_2$	$\frac{\alpha_3}{2^3} 3y_1^2 y_2$
$G_{-2,1}(\cdot), -2\omega_1 + \omega_2$ (if $\omega_2 \geq 2\omega_1$)	$\frac{\alpha_3}{2^3} 3y_1^{2*} y_2$
$G_{1,2}(\cdot), \omega_1 + 2\omega_2$	$\frac{\alpha_3}{2^3} 3y_1 y_2^2$
$G_{-1,2}(\cdot), -\omega_1 + 2\omega_2$	$\frac{\alpha_3}{2^3} 3y_1^* y_2^2$

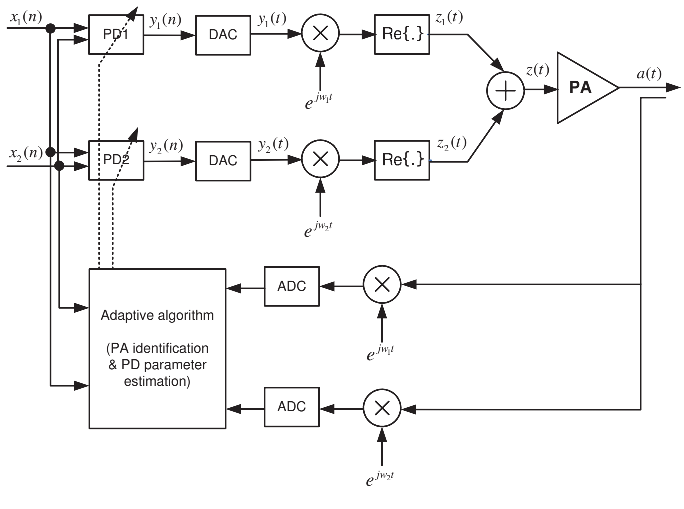

Fig. 3. Proposed PD structure.

III. Development of Proposed PD

Since the cross-products between band 1 and band 2 signals appear in both ω_1 and ω_2, the predistorter also requires $x_1(n)$ and $x_2(n)$ for predistortion. Based on this intuition, we propose a predistortion structure as shown in Fig. 3. $F_1(\cdot)$ and $F_2(\cdot)$ are predistortion functions for linearization of the band 1 and band 2 signals, respectively. In the proposed structure, the PD problem can be written as

$$a_1(n) \triangleq G_1(F_1(x_1(n), x_2(n)), F_2(x_1(n), x_2(n))) = K_o x_1(n)$$
$$a_2(n) \triangleq G_2(F_1(x_1(n), x_2(n)), F_2(x_1(n), x_2(n))) = K_o x_2(n)$$

where K_o is the desired gain of the PA. The PD parameters are found through two steps: one is PA identification and the other is PD parameter calculation. Considering the PD problem, two predistorter outputs are linked together at each band of the PA output as explained in Section II. Thus, two PD parameters also depend on each other, which makes it difficult to find the PD parameters separately. As an alternative method, we propose an iterative method to find the PD parameters.

A. PA identification

In this step, the baseband digital PA models $G_i(\cdot)$ for $i = 1, 2$ are estimated. Denote $G_k(y_1(nT),\ y_2(nT))$ where T is the sampling period as $G_k(y_1(n), y_2(n))$ for simplicity. From Table I, $G_1(y_1(n), y_2(n))$ can be written as

$$G_1(y_1(n), y_2(n)) = \mathbf{w}_1^T(n)\mathbf{u}_1(n)$$

where $\mathbf{w}_1(n)$ is a 3×1 weight vector to be estimated and $\mathbf{u}_1(n) = [y_1(n), y_1(n)|y_1(n)|^2,\ y_1(n)|y_2(n)|^2]^T$. Similarly, $G_2(\cdot)$ can be expressed as

$$G_2(y_1(n), y_2(n)) = \mathbf{w}_2^T(n)\mathbf{u}_2(n)$$

where $\mathbf{w}_2(n)$ is 3×1 weight vector and $\mathbf{u}_2(n) = [y_2(n), y_2(n)|y_2(n)|^2, y_2(n)|y_1(n)|^2]^T$. For estimation of the weight vectors, $\mathbf{w}_1(n)$ and $\mathbf{w}_2(n)$, we choose to minimize the mean square errors. Then, the cost functions are

$$\mathcal{E}_{\mathbf{w}_i} = \mathrm{E}[|e_{\mathbf{w}_i}(n)|^2] \ \text{ for } \ i = 1, 2$$

where $e_{\mathbf{w}_i}(n) = a_i(n) - \mathbf{w}_i^T(n)\mathbf{u}_i(n)$ and $a_i(n)$ is the baseband digital signal for i-th feedback path in Fig. 3. The weight vectors minimizing the cost functions can be found via the adaptive least mean squares (LMS) algorithm [7]:

$$\mathbf{w}_i(n+1) = \mathbf{w}_i(n) + \mu_i e^*_{\mathbf{w}_i}(n)\mathbf{u}_i \ \text{ for } \ i = 1, 2$$

where $\{\mu_i\}$ are the step sizes.

B. Predistortion

After identifying the PA, the PD parameters are calculated. The PD outputs for band 1 and band 2 can be represented as follows:

$$y_1(n) = F_1(x_1(n), x_2(n)) = \mathbf{p}_1^T\mathbf{v}_1(n),$$
$$y_2(n) = F_2(x_1(n), x_2(n)) = \mathbf{p}_2^T\mathbf{v}_2(n),$$

where $\mathbf{p}_1$ and $\mathbf{p}_2$ are 5×1 predistortion vectors to be found and $\mathbf{v}_1(n) = [x_1(n), x_1(n)|x_1(n)|^2, x_1(n)|x_2(n)|^2, x_1(n)|x_1(n)|^4, x_1(n)|x_2(n)|^4]^T$ and $\mathbf{v}_2(n) = [x_2(n), x_2(n)|x_2(n)|^2, x_2(n)|x_1(n)|^2, x_2(n)|x_2(n)|^4, x_2(n)|x_1(n)|^4]^T$. The choice of $\{\mathbf{v}_i(n)\}$ is not unique and there are many possible candidates. Referring to table I, $y_1(n)$, $y_1(n)|y_1(n)|^2$, and $y_1(n)|y_2(n)|^2$ contribute to ω_1, and $y_2(n)$, $y_2(n)|y_2(n)|^2$, and $y_2(n)|y_1(n)|^2$ contribute to ω_2. To combat those nonlinear products, the higher order signal components are considered in $\{\mathbf{v}_i(n)\}$. To find the PDs, we define a cost function as follows:

$$\mathcal{E}(n) = E\left[\lambda_1|e_1(n)|^2 + \lambda_2|e_2(n)|^2\right]$$

where $e_1(n) = x_1(n) - \mathbf{w}_1^H\mathbf{u}_1(n)$ and $e_2(n) = x_2(n) - \mathbf{w}_2^H\mathbf{u}_2(n)$. λ_1 and λ_2 are weighting factors. An adaptive algorithm for updating the coefficient $\mathbf{p}_1$ for band 1 is obtained by applying the stochastic gradient method [7]:

$$\begin{aligned}\hat{\mathbf{p}}_1(n+1) &= \hat{\mathbf{p}}_1(n) - \frac{1}{2}\mu_{p1}\frac{\partial\mathcal{E}(n)}{\partial\mathbf{p}_1(n)} \\ &= \hat{\mathbf{p}}_1(n) - \frac{1}{2}\mu_{p1}\left\{\lambda_1\frac{\partial|e_1(n)|^2}{\partial\mathbf{p}_1(n)} + \lambda_2\frac{\partial|e_2(n)|^2}{\partial\mathbf{p}_1(n)}\right\}\end{aligned} \tag{2}$$

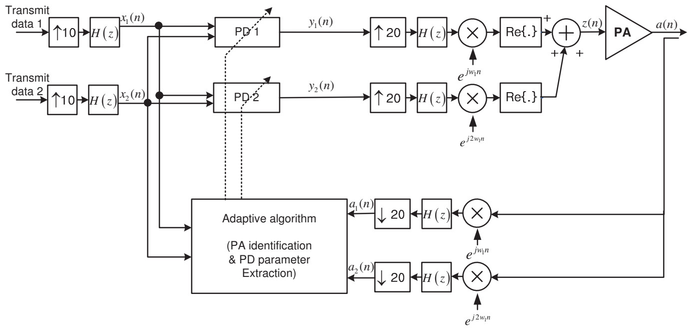

Fig. 4. Simulation model of the proposed PD.

Similarly, the adaptive algorithm for band 2 can be written as

$$\begin{aligned}\hat{\mathbf{p}}_2(n+1) &= \hat{\mathbf{p}}_2(n) - \frac{1}{2}\mu_{p2}\frac{\partial\mathcal{E}(n)}{\partial\mathbf{p}_2(n)} \\ &= \hat{\mathbf{p}}_2(n) - \frac{1}{2}\mu_{p2}\left\{\lambda_1\frac{\partial|e_1(n)|^2}{\partial\mathbf{p}_2(n)} + \lambda_2\frac{\partial|e_2(n)|^2}{\partial\mathbf{p}_2(n)}\right\}.\end{aligned} \tag{3}$$

Note that updating $\mathbf{p}_1(n)$ requires $\mathbf{p}_2(n)$ because both $e_1(n)$ and $e_2(n)$ are functions of $\mathbf{p}_1(n)$ and $\mathbf{p}_2(n)$, and vice versa. Thus, $\mathbf{p}_1(n)$ and $\mathbf{p}_2(n)$ cannot be solved separately. As an alternative method, an iterative method is proposed. At the start, $\mathbf{p}_1(1) = \mathbf{p}_2(1) = [1, 0, ..., 0]^T$. Then, obtain $\mathbf{p}_1(2)$ by fixing $\mathbf{p}_2(1)$. After that, calculate $\mathbf{p}_2(2)$ by fixing $\mathbf{p}_1(2)$. Repeating the similar process, the iteration is performed until both $\mathbf{p}_1(n)$ and $\mathbf{p}_2(n)$ converge. Those iteration methods can reduce the cost function as n increases. However, it does not always guarantee the global optimality of the solution. Verification of the optimality is our further work.

IV. Simulation Results

The performance of the proposed PD is examined through computer simulation. Simulation environments are as follows. Two transmitted data are generated independently. The transmitted data are modulated by 16 quadrature amplitude modulation (16-QAM) and pulse-shaped by a square root raised cosine filter with roll-off 0.25. The sampling clock of the pulse shaping filter (PSF) output is 10 times the symbol rate. The PSF output is predistorted by the proposed PD. For simulating the analog up/down-converter and analog PA in digital domain, we further interpolate the PD output by a factor of 20 and the analog parts are modeled by digital filters. The carrier frequency is $\omega_1 = 2\pi \times 10F_s$ and $\omega_2 = 2\pi \times 42F_s$ where F_s is the symbol rate. The PA model is $a(n) = z(n) - 0.8z^2(n) + 0.7z^3(n)$.

A. Performance of PA identification

The identification performances for $\{G_i(\cdot)\}$ are examined. The initial conditions for the parameters $\{\mathbf{w}_i\}$ are $[1/2, 0, 0, \cdots, 0]^T$, and the stepsizes $\{\mu_i\}$ are 0.1. Figs. 5 show the learning curves for the mean square errors (MSEs), $\mathrm{E}[|a_i(n) - \mathbf{w}_i(n)\mathbf{u}(n)|^2]$ for $i = 1, 2$. The learning curves are obtained by averaging 50 independent trials. According

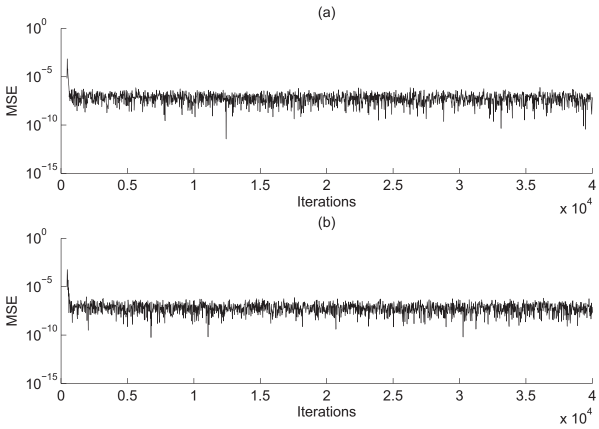

Fig. 5. Learning curves for estimation of $G_1(\cdot)$ and $G_2(\cdot)$.

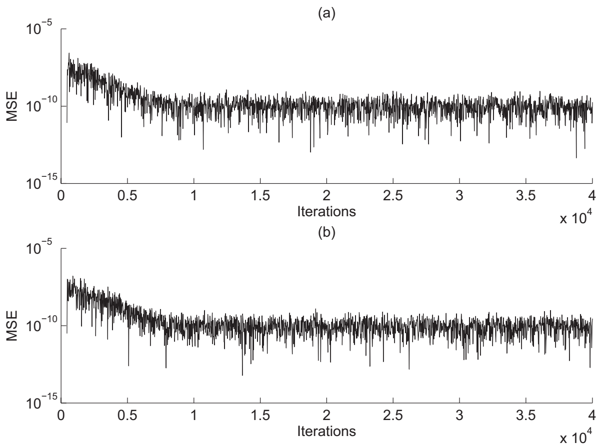

Fig. 6. Learning curves for $\mathrm{E}[|e_{\mathbf{p}_1}(n)|^2]$ and $\mathrm{E}[|e_{\mathbf{p}_2}(n)|^2]$.

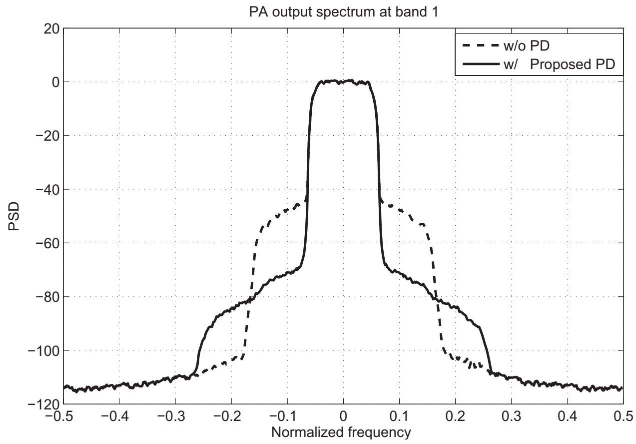

Fig. 7. PA output spectrum at ω_1.

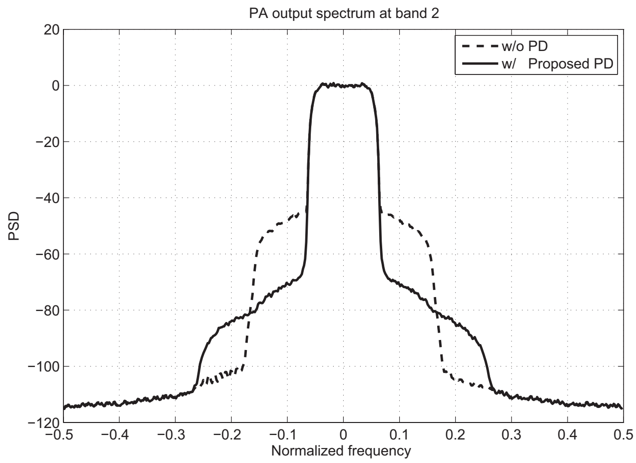

Fig. 8. Output spectrum at ω_2.

to the results, the adaptive algorithms converge within 5,000 iterations, and the MSE after convergence is around 10^{-7}.

B. PD Performance

After PA identification, the parameters of PDs are obtained. $[0, 0, 0, \cdots, 0]^T$ are used for the initial conditions of $\{\mathbf{p}_i\}$, the step sizes are 5, and $\{\lambda_i\} = 0.5$. Figs. 6 show the learning curves for the MSEs. The iterative algorithm converges after 1×10^4 iterations. Figs. 7–8 show the spectrum performance around ω_1 and ω_2, respectively. The spectrum is obtained from the PA output after 4×10^4 iterations. Without PD, two bands interfere with each other, which results in large spectral regrowth. However, by applying the proposed PD, the PA is notably linearized and the spectral regrowth is significantly suppressed. It is shown that the spectral regrowth of the band1 and band2 are reduced by 20dB. These results indicate that the proposed method is effective for linearizing multi-band signals.

V. Conclusion

A new predistortion scheme for multi-band signals was proposed. The proposed PD structure has multiple PDs (one PD for one band). Since multiple PD parameters are linked together, an iterative algorithm to find the PD parameters was proposed. Computer simulation showed that the proposed method can effectively suppress the spectral regrowth of the multiple bands signals, and compensates for the nonlinearity of the PA.

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