Simplified Online Coefficients Updating for Digital Predistortion of Wideband/Multi-band RF Power Amplifiers

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Abstract- **In this paper, a simplified online coefficients updating technique is proposed to realize real-time tuning of digital predistortion (DPD) for RF power amplifiers (PAs), particularly focusing on wideband and concurrent multi-band scenarios. It is achieved by equally weighting the memory terms in conventional DPD models that leads to a significant reduction of numerical calculation complexity in the coefficients updating process and thus saves time and power during real system operation. To validate the proposed method, both wideband LTE-A (100 MHz) and concurrent dual-band (20 MHz + 20 MHz) cases have been tested. Experimental results show that the proposed method can achieve excellent performance with significant reduction of system complexity compared to the conventional approaches.**

Index Terms- **Digital predistortion, dual-band, model extraction, on-line updating, power amplifier, wideband.**

I. INTRODUCTION

As one of the most popular linearization solutions for RF power amplifiers (PA), digital predistortion (DPD) allows the PA to be operated at a high driven level for high efficiency without sacrificing transmission accuracy. DPD is based on the principle of nonlinear inversion. In other words, only if the transfer function of the DPD is the exact inverse of that of the PA, a linear amplification can be achieved at the final output. The DPD coefficients can be extracted at start up, but the transfer function of a PA is often affected by the operating environment changes, e.g., drain bias drifts or temperature variations. In order to maintain the performance, the DPD coefficients must be updated properly during the real-time operation.

The most commonly employed methods can be roughly categorized into two groups. The first one is to update the entire coefficients set by re-running the full model extraction module. The second approach is to employ a fine tuning block to only update the changes of the coefficients, similar to the solution used in the dual-loop model extraction structure in [1]. Because the structure of the DPD model remains the same in the updating operation, both approaches require complex numerical calculation, i.e., the least squares (LS) matrix inversion, which consumes significant power and time during the coefficients updating process. With the deployments of wideband [2] and multi-band [3] DPD in modern communications systems, the situation becomes worse since the DPD models will become much more complex. To resolve this issue, this paper proposes a simplified DPD coefficients updating method to accommodate the DPD development for wideband and concurrent multi-band systems. By further simplifying the fine tuning block in the coefficients updating process [1], the complexity can be greatly reduced while keeping similar linearization performance, leading to a cost-effective solution.

II. CONVENTIONAL DPD ONLINE UPDATING

Generally, DPD models can be expressed by using the popular discrete time-domain Volterra series. Here, we take the 1st-order DDR-Volterra model as an example, that is,

$$\begin{aligned}\tilde{u}(n) = &\sum_{p=0}^{(P-1)/2}\sum_{m=0}^{M} c_{2p+1,1}(m)\left|\tilde{x}(n)\right|^{2p}\tilde{x}(n-m)\\ &+\sum_{p=1}^{(P-1)/2}\sum_{m=1}^{M} c_{2p+1,2}(m)\left|\tilde{x}(n)\right|^{2(p-1)}\tilde{x}^{2}(n)\tilde{x}^{*}(n-m)\end{aligned}\quad, \qquad (1)$$

where $\tilde{x}(n)$ and $\tilde{u}(n)$ represents the input and output of the DPD model, respectively, and $c_{2p+1,j}$ (j=1 or 2) represents the coefficients. For better illustration, (1) can be written in matrix form, that is,

$$\mathbf{U} = \mathbf{XC}, \qquad (2)$$

where **C** is the coefficients vector, **U** is the output vector generated from $\tilde{u}(n)$, and **X** is the regression matrix constructed from the terms in the model, such as

$$\left[\tilde{x}(n),\tilde{x}(n-1),...,\left|\tilde{x}(n)\right|^{2}\tilde{x}(n-1)\ ,...,\ \left|\tilde{x}(n)\right|^{2p}\tilde{x}(n-M)\right]. \qquad (3)$$

Since the PA behavior can change during the real system operation, **C** needs to be frequently updated. Like the method in [1], in order to update the coefficient efficiently, it is not necessary to re-calculate the coefficients set totally, only the changed part **ΔC** is required to be extracted,

$$\mathbf{C}_{new} = \mathbf{C} + \Delta\mathbf{C}\ . \qquad (4)$$

And the PA behavior change can be represented by

$$\Delta\mathbf{U} = \mathbf{X}\Delta\mathbf{C} \approx \mathbf{e}\,, \qquad (5)$$

which can be approximated by the linearization error, that is defined as **e**=[$\tilde{x}(1)$ - $\tilde{y}(1)$,…, $\tilde{x}(N)$ - $\tilde{y}(N)$]. Due to the linear-in-parameters property, the LS method can be employed to extact **ΔC**,

$$\Delta\mathbf{C} = \left(\mathbf{X}^{H}\mathbf{X}\right)^{-1}\mathbf{X}^{H}\Delta\mathbf{U}. \qquad (6)$$

Because matrix inversion operation is involved and the complexity of this operation heavily depends on the size of ($\mathbf{X}^H\mathbf{X}$) that is related to the number of the terms in (3), this updating process consumes significant amount of power and time. Particularly, in wideband and multi-band scenarios, the situation will become much worse. That is because, in the wideband case, stronger memory effects will appear and thus more coefficients will be required. While, in the multi-band scenario, multiple sets of coefficients will be employed and the coefficients number of each set will be expanded. Both cases implied that a more efficient coefficient updating technique is required to be developed to accommodate complex scenarios.

III. Simplified DPD Online Updating

Fortunately, in online updating process, since the level of PA behavior change is usually smaller compared to the original one, e.g., only a couple of dB increase of the adjacent channel power ratio (ACPR), it is reasonable to employ a simpler model to compensate this change with much lower complexity. In a general behavioral model, the model terms can be categorized into two different parts: the memory-less terms that represent the PA gain compression or expansion and the memory terms that describe the dynamic changes. Equation (5) can then be decomposed into

$$\Delta\mathbf{U} = \left[\mathbf{X}_{ml}\ \mathbf{X}_{m}\right]\Delta\mathbf{C}, \tag{7}$$

where *ml* and *m* stand for the memory-less and memory components, respectively. The $\mathbf{X}_{ml}$ represents the memoryless terms. Take the terms in (3) for example, such as

$$\left[\tilde{x}(n), |\tilde{x}(n)|^2 \tilde{x}(n), ..., |\tilde{x}(n)|^{2p} \tilde{x}(n)\right]. \tag{8}$$

Normally, the memory-less terms that characterize the static nonlinearity of the PA are considered as the major contribution during the modeling process. $\mathbf{X}_m$ represents the memory terms, such as

$$\left[|\tilde{x}(n)|^{2p} \tilde{x}(n-1), ..., |\tilde{x}(n)|^{2p} \tilde{x}(n-M)\right]. \tag{9}$$

Usually it has less contribution compared to that of the memory-less part. Especially, in the online updating procedure, the contribution for the memory terms is even smaller, due to the slight change of PA behavior. Hence, the modeling of the behavior change $\Delta\mathbf{U}$ can be approximated by equally treating the contribution of the memory terms within the same nonlinear order. That is, (9) can be averaged into one term to represent the simplified memory terms $\mathbf{X}_{m,sim}$, as shown in (10),

$$\frac{1}{M}\sum_{m=1}^{M} |\tilde{x}(n)|^{2p} \tilde{x}(n-m). \tag{10}$$

After applying this approach to all memory terms, (7) can be simplified as:

$$\Delta\mathbf{U} = \left[\mathbf{X}_{ml}\ \mathbf{X}_{m,sim}\right]\Delta\mathbf{C} = \mathbf{X}_{sim}\Delta\mathbf{C}. \tag{11}$$

And the coefficients can be extracted by LS:

$$\Delta\mathbf{C} = \left(\mathbf{X}_{sim}^H \mathbf{X}_{sim}\right)^{-1} \mathbf{X}_{sim}^H \Delta\mathbf{U}, \tag{12}$$

where $\mathbf{X}_{sim}$ represents the new simplified regression matrix. Because the model has been considerably simplified, the size of the inverse matrix in (12) is much smaller than the one in (6). Therefore, the complexity of the DPD on-line updating is greatly reduced. Based on the new model, the proposed on-line updating process can be illustrated as shown in Fig. 1. Once the PA behaviour is changed, the error signal will be calculated instantly. Simultaneously, the input signal will be used to construct the simplified model according to the method above. After the extraction of $\Delta\mathbf{C}$, the new DPD coefficients can then be updated according to (4).

Based on the above discussion, we can apply this idea in DPD coefficient updating for two more complex scenarios: the wideband scenario with limited bandwidth [2] and the concurrent dual-band scenario [3].

In wideband cases, the PA behavior change can be represented by

$$\begin{aligned}\Delta\tilde{u}(n) = &\sum_{p=0}^{(P-1)/2}\sum_{m=0}^{M} \Delta c_{2p+1,1}(m) |\tilde{x}(n)|^{2p} \tilde{x}(n-m) \otimes w(n) \\ &+ \sum_{p=1}^{(P-1)/2}\sum_{m=1}^{M} \Delta c_{2p+1,2}(m) |\tilde{x}(n)|^{2(p-1)} \tilde{x}^2(n) \tilde{x}^*(n-m) \otimes w(n).\end{aligned} \tag{13}$$

where $w(n)$ represented the band-limited function. By applying the proposed simplification, we can obtain

$$\begin{aligned}\Delta\tilde{u}(n) = &\sum_{p=0}^{(P-1)/2} \Delta c_{2p+1,1}^{(0)} |\tilde{x}(n)|^{2p} \tilde{x}(n) \otimes w(n) \\ &+ \sum_{p=0}^{(P-1)/2} \Delta c_{2p+1,1}^{(1)} |\tilde{x}(n)|^{2p} \sum_{m=0}^{M} \tilde{x}(n-m) \otimes w(n) \\ &+ \sum_{p=1}^{(P-1)/2} \Delta c_{2p+1,2}^{(1)} |\tilde{x}(n)|^{2(p-1)} \tilde{x}^2(n) \sum_{m=1}^{M} \tilde{x}^*(n-m) \otimes w(n).\end{aligned} \tag{14}$$

Also, in concurrent dual-band cases, the proposed method can be employed to the 2-D MP model. The PA behavior change in this model can be expressed as:

$$\begin{cases}\Delta\tilde{u}_1(n) = \displaystyle\sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M-1} c_{p,k,1}^{(0)} \tilde{x}_1(n-m) \times |\tilde{x}_1(n-m)|^{p-k} |\tilde{x}_2(n-m)|^{k} \\ \Delta\tilde{u}_2(n) = \displaystyle\sum_{p=0}^{P}\sum_{k=0}^{p}\sum_{m=0}^{M-1} c_{p,k,2}^{(0)} \tilde{x}_2(n-m) \times |\tilde{x}_2(n-m)|^{p-k} |\tilde{x}_1(n-m)|^{k},\end{cases} \tag{15}$$

where $\tilde{x}_1(n)$, $\tilde{x}_2(n)$ and $\tilde{u}_1(n)$, $\tilde{u}_2(n)$ represents the input and output of the 2D-DPD model. And $c_{p,k,j}$ (j=1 or 2) is the coefficient. After the simplification, we can obtain:

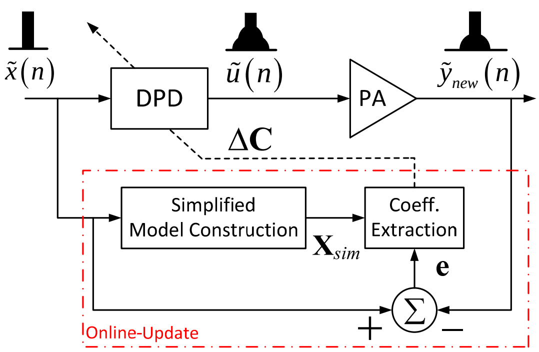

Fig. 1. Proposed DPD updating approach

$$
\begin{cases}
\Delta\tilde{u}_1(n)=\sum_{p=0}^{P}\sum_{k=0}^{p}c_{p,k,i}^{(0)}\tilde{x}_1(n)\times\left|\tilde{x}_1(n)\right|^{p-k}\left|\tilde{x}_2(n)\right|^{k} \\
\quad+\sum_{p=0}^{P}\sum_{k=0}^{p}c_{p,k,j}^{(1)}\sum_{m=1}^{M-1}\tilde{x}_1(n-m)\times\left|\tilde{x}_1(n-m)\right|^{p-k}\left|\tilde{x}_2(n-m)\right|^{k} \\
\Delta\tilde{u}_2(n)=\sum_{p=0}^{P}\sum_{k=0}^{p}c_{p,k,i}^{(0)}\tilde{x}_2(n)\times\left|\tilde{x}_2(n)\right|^{p-k}\left|\tilde{x}_1(n)\right|^{k} \\
\quad+\sum_{p=0}^{P}\sum_{k=0}^{p}c_{p,k,j}^{(1)}\sum_{m=1}^{M-1}\tilde{x}_2(n-m)\times\left|\tilde{x}_2(n-m)\right|^{p-k}\left|\tilde{x}_1(n-m)\right|^{k}.
\end{cases} \quad (16)
$$

IV. Experimental Results

To fully validate the proposed updating technique, a high power LDMOS Doherty operated at 2.14 GHz is tested based on the platform in [4]. To emulate the PA behavior change, the drain bias of the PA was reduced by 2.5 V from the original 28 V. The tests were conducted for the following two cases:

A. *Wideband LTE-A Signal Test*

A 100 MHz LTE-A signal with 7.8 dB peak to power ratio (PAPR) was employed in this case. The proposed technique is applied to the 2nd order DDR band limited model with a nonlinear order of 9 and a memory length of 5. The measured normalized power spectral density (PSD) is shown in Fig. 2 (a) and the normalized mean square error (NMSE) performance are shown in the TABLE I.

Due to the change of the bias, the PA nonlinear pattern has been seriously manipulated, leading to in-tolerable nonlinearity regrowth that can be reflected by the PSD. The NMSE value is also increased by almost 10 dB. By using the proposed updating technique, the PA nonlinearity change can be effectively compensated, leading to the same level of linearization performance as the one achieved by the conventional approach. For the conventional approach, we are required to extract 90 coefficients, while only 30 coefficients need to be extracted in the proposed one.

B. *LTE and WCDMA Dual-band Signal Test*

In this part, a 20MHz LTE and 20MHz WCDMA dual-band signal with 60 MHz frequency gap and 9.2 dB PAPR is tested to further validate the proposed updating technique. The 2-D MP model is employed here with nonlinear order 6 and memory length 5. The measurement results are shown in Fig 2 (b), (c) and Table I. Similar to the wideband test, the change of the bias can induce about 10 dB increase of the ACPR and NMSE for each band, indicating a great amount of distortion regrowth. This type of nonlinearity can be almost fully compensated by the proposed approach in (16) with only 42 coefficients for each band. For the conventional method, 105 coefficients each band are required in order to obtain same linearity level.

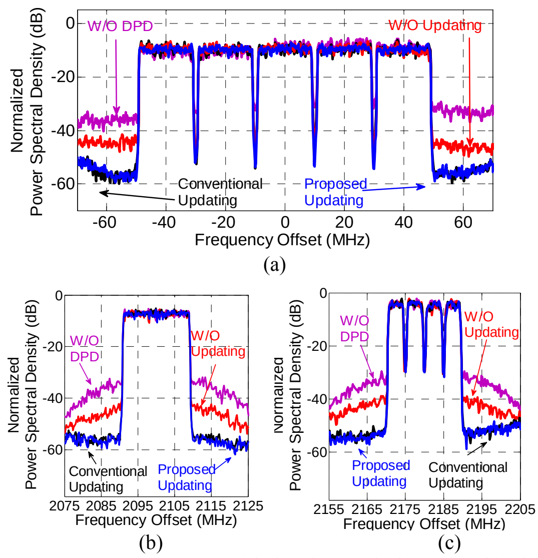

Fig. 2. Measurement PSD: (a) wide-band case; (b) lower band in dual-band case; (c) upper band in dual-band case.

V. Conclusion

In this paper, a simplified online DPD coefficients updating method was proposed. By decoupling the change pattern of the PA behavior and using a simplified model to compensate it, the PA nonlinearity regrowth during online operation can be effectively removed, leading to a low complexity yet effective solution for future wideband and multi-band scenarios.

Acknowledgments

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TABLE I
THE PERFORMANCE OF COMPARISON WITH PROPOSED METHOD AND CONVENTIONAL METHOD

	NMSE (dB)			No. Coeff.	
	Wide-band	Dual-band		Wide-band	Dual-band
		Lower Band	Upper Band		
Without Updating	-26.56	-28.45	-30.77	N/A	N/A
Proposed Updating	-40.90	-40.93	-39.91	30	42*2
Conventional Updating	-41.08	-40.54	-40.33	90	105*2