



Robust Digital Predistortion for LTE/5G Power Amplifiers Utilizing Negative Feedback Iteration

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Abstract: A robust digital predistortion (DPD) technique utilizing negative feedback iteration is introduced for linearizing power amplifiers (PAs) in long term evolution (LTE)/5G systems. Different from the conventional direct learning and indirect learning structure, the proposed DPD suggests a two-step method to identify the predistortion. Firstly, a negative feedback based iteration is used to estimate the optimal DPD signal. Then the corresponding DPD parameters are extracted by forward modeling with the input signal and optimal DPD signal. The iteration can be applied to both single-band and dual-band PAs, which will achieve superior linear performance than the conventional direct learning DPD while having a relatively low computational complexity. The measurement is carried out on a broadband Doherty PA (DPA) with a 200 MHz bandwidth LTE signal at 2.1 GHz, and on a 5G DPA with two 10 MHz LTE signals at 3.4/3.6 GHz for validation in dual-band scenarios.

Keywords: 5G; digital predistortion; power amplifiers; negative feedback iteration

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1 Introduction

In order to accommodate the growing demands of massive applications, modern wireless communication systems must evolve to provide higher data capacity and bit rate, and support multiple subscribers simultaneously. These requirements motivate the application of broadband modulated signals and concurrent multi-band transmission. In the forthcoming 5G era, the bandwidth requirements for transmission signals in sub-6 GHz frequency band and millimeter

wave band are up to 200 MHz and 800 MHz, respectively.

As one of the key devices in radio frequency (RF) transmitters, the power amplifiers (PAs) are characterized as the most power-hungry components and their performance will directly affect the efficiency of RF transmitters. In modern communication system, high efficiency and linearity are two basic requirements for PAs. In order to acquire higher efficiency, the PA should be operated close to the saturation region, inevitably leading to strong nonlinear distortion. In the 5G communication system, the linearity requirements for the highly efficient PAs operated near the saturation region become even more stringent due to the application of broadband modulated bandwidth or concurrent multi-band transmission. Effective PA linearization techniques must be employed.

Digital predistortion (DPD) is the most popular PA linear-

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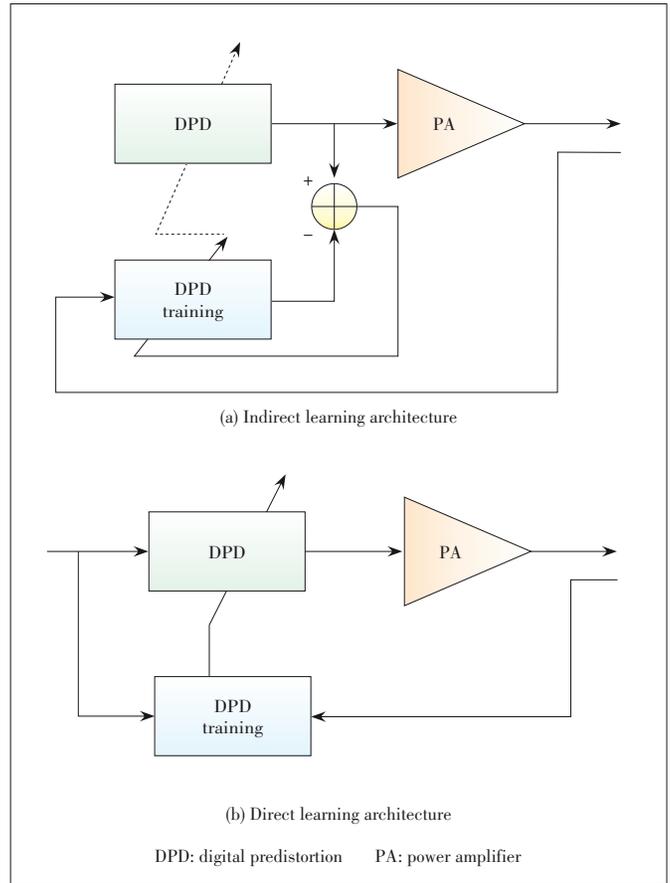
ization technique in the current 4G system. Based on accurate behavioral modeling, DPD can predict PA’s nonlinear behavior and eliminate them by adding a proper correction signal^[1-6]. Due to the significant linearization performance and moderate hardware cost, the DPD technique is still one of the promising linearization solutions in 5G applications.

There are two common adaptive learning structures for DPD parameter extraction, that is, the direct learning (DL) architecture and the indirect learning (IDL) architecture^[7-8]. **Fig. 1** depicts the block diagrams of DL and IDL structures. The IDL estimates the post-inverse model of PA and copies it as the predistorter, thus, the linear performance is limited since the noise at PA’s output will be inevitably introduced in the parameter identification^[9]. Moreover, the IDL provides compromised linearization performance when the PA is highly compressed, and generates DPD signals with high peak-to-average power ratio (PAPR) which might cause damage to the PAs. The DL algorithm, which is based on the pre-inverse model of PA, is more robust and provides more precise parameter identification than IDL^[10]. However, since several iterations are needed before the DL algorithm converges to the optimal parameters, the DL estimation is more computationally expensive and complex in structure. In the broadband application scenario, the number of DPD parameters will be further increased in order to compensate the stronger nonlinear distortion, leading to the lower convergence speed and considerable calculation.

In Ref. [5], the concept of iterative learning control for the linearization of PAs is introduced, which provides a new perspective for DPD parameter extraction. Ref. [11] proposes a negative feedback iteration based digital predistortion to linearize the broadband PAs. In this paper, we present a more explicit investigation of the methodology and experimental results of the negative feedback iteration based DPD, and extend the technique to the multi-band scenario. The proposed DPD can realize superior linear performance in broadband application scenarios than conventional DL DPD while having a relatively low computational complexity. Furthermore, the proposed DPD can be prompted to the dual-band scenario. The measurements are performed on a broadband Doherty PA (DPA) with a 200 MHz bandwidth long term evolution (LTE) signal at 2.1 GHz, and on a DPA for 5G application with two 10 MHz LTE signals at 3.4/3.6 GHz carrier frequency to validate the performance of the proposed DPD technique.

2 Proposed DPD Technique Utilizing Negative Feedback Iteration

The block diagram of negative feedback iteration based DPD technique in single band scenario is presented in **Fig. 2**, where the proposed DPD method can be divided into two major steps. Firstly constructing a negative feedback iteration to obtain the optimal input signal of PA, which can be regarded



▲ **Figure 1. Indirect learning (IDL) and direct learning (DL) architectures.**

as DPD signal, and then calculating the parameters of DPD module utilizing the original input signal and the optimal input signal obtained in the first step.

2.1 Negative Feedback Iteration

According to the changes of output, the feedback can be divided into two categories: the positive feedback (which increases the output changes) and the negative feedback (which decreases the output changes). It is obvious that the output of PA will be more stable utilizing the negative feedback.

One of the simplest negative feedback structure is injecting the error between normalized output and input to the system as the new input. In the proposed method, the input signal in the previous iteration is considered, as presented in **Fig. 3**, which indicates that the input in the k -th iteration as:

$$x_k(n) = x_{k-1}(n) + w_0(u(n) - \lambda \tilde{y}_k(n)), \quad (1)$$

where $x_k(n)$ and $\tilde{y}_k(n)$ denote the normalized input and output of PA in the k -th iteration, and $u(n)$ is the original input signal. λ denotes the feedback depth, and w_0 is a control factor used to adjust the convergence of negative feedback iteration.

According to Eq. (1), the input signal of PA will be modified after each iteration. Since it is a negative feedback sys-

tem, the changes of output signal will decrease during the iteration and eventually tend to zero. However, due to the nonlinear behavior of PA, the output tends to be unchanged when the error between original input and output tends to be zero, that is, $u(n) - \lambda \tilde{y}_{k-1}(n) \approx 0$, which indicates that a linearized output will be obtained from the iteration format as in Eq. (1). At that time, the input signal of PA will also tend to be stable and have nonlinear relationship with the original input to produce the linear output.

2.2 DPD Parameter Extraction

The principle of DPD is to construct a nonlinear module cascaded before PA to linearize the output signal of PA. Therefore, the optimal input signal obtained in the negative feedback iteration can be regarded as the DPD signal. The input and output signal of DPD module can be expressed utilizing generalized memory polynomial (GMP) model^[5], as shown in Eq. (2).

$$\begin{aligned}
 x_{DPD}(n) = & \sum_{k=1}^{K_c} \sum_{m=0}^{M_c} a_{km} u(n-m) |u(n-m)|^{k-1} + \\
 & \sum_{k=1}^{K_b} \sum_{m=0}^{M_b} \sum_{l=1}^{L_b} b_{kml} u(n-m) |u(n-m-l)|^{k-1} + \\
 & \sum_{k=1}^{K_c} \sum_{m=0}^{M_c} \sum_{l=1}^{L_c} c_{kml} u(n-m) |u(n-m+l)|^{k-1},
 \end{aligned} \quad (2)$$

where $K_{a,b,c}$ and $M_{a,b,c}$ denote the nonlinear order and memory depth, and L_a and L_b are the lagging and leading depth, respectively.

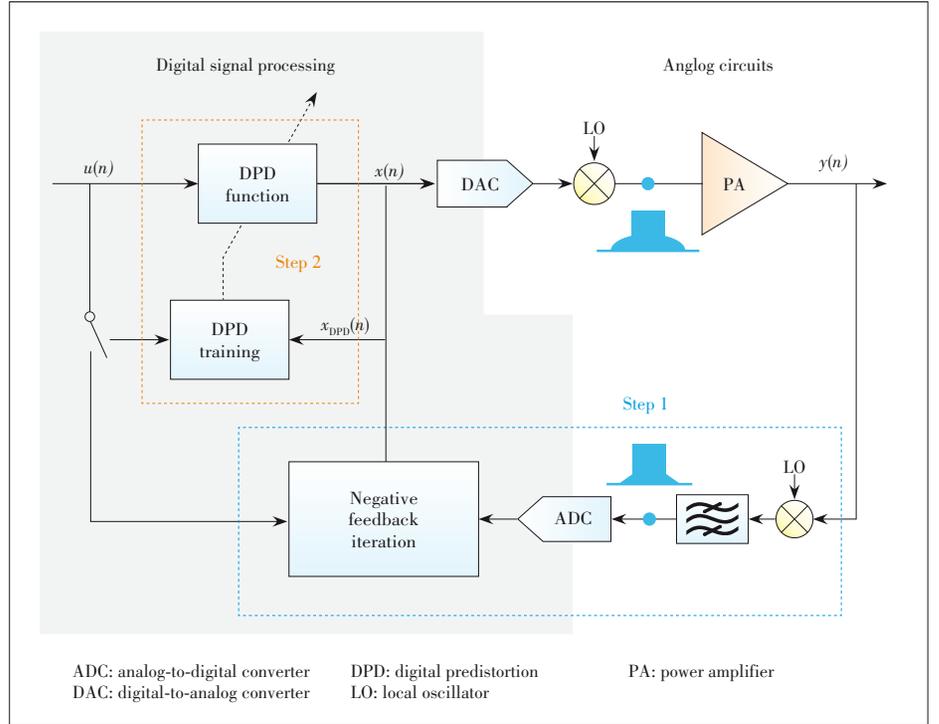
In DL DPD, the iteration format of DPD parameters \mathbf{b} with least square (LS) algorithm can be written as:

$$\mathbf{b}^{k+1} = \mathbf{b}^k + \mu (\mathbf{A}^H \mathbf{A})^{-1} \mathbf{A}^H (\mathbf{u} - \mathbf{y}^k), \quad (3)$$

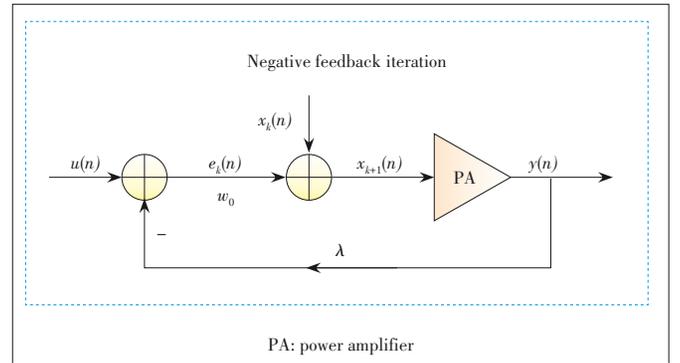
where \mathbf{A} is the basis function matrix composed of original input; \mathbf{u} and \mathbf{y} denote original input and PA output signal column vector. Therefore, the DPD signal at k -th iteration has the form as:

$$\begin{aligned}
 \mathbf{x}_{DPD_DL}^k &= \mathbf{A} \mathbf{b}^k \\
 &= \mathbf{x}_{DPD_DL}^{k-1} + \mu \mathbf{A} (\mathbf{A}^H \mathbf{A})^{-1} \mathbf{A}^H (\mathbf{u} - \mathbf{y}^k).
 \end{aligned} \quad (4)$$

Let $\lambda = 1$, which indicates that the whole information of output signal is applied to the input, and the k -th DPD signal of



▲ Figure 2. Structure of the negative feedback iteration based DPD technique in single-band scenario.



▲ Figure 3. Proposed negative feedback loop for iteration.

proposed DPD can be written as:

$$\mathbf{x}_{DPD_NF}^k = \mathbf{x}_{DPD_NF}^{k-1} + w_0 (\mathbf{u} - \mathbf{y}^k). \quad (5)$$

It appears that Eqs. (4) and (5) have the same iteration form under the case that the precise inverse matrix of \mathbf{A} can be obtained. However, since the condition number of basis function matrix \mathbf{A} increases dramatically with the increasing of parameters^[12], the calculated inverse matrix is inaccurate which could enlarge the iteration error and the parameter accuracy would deteriorate in the next iteration. Therefore, the DPD signal obtained in the negative feedback iteration, which has eliminated the numerical error, can be regarded as the optimal DPD signal.

Once the optimal DPD signal is identified, the parameters

of DPD module can be estimated using LS algorithm with the original input and DPD signal, as in Eq. (6).

$$\mathbf{b}_p = (\mathbf{A}^H \mathbf{A})^{-1} \mathbf{A}^H \mathbf{x}_{DPD}, \quad (6)$$

where \mathbf{b}_p denotes the coefficients of the predistorter, and \mathbf{A} is composed of the basis functions in Eq. (2) with the original input signal $u(n)$.

Furthermore, another merit of the proposed DPD is the relatively low computational complexity. As it can be seen in Eq. (6), only once the parameter calculation is needed with the proposed DPD, while in the DL DPD the parameter calculation is needed in each iteration. Therefore, if the iteration times of both DPD schemes are equivalent, the computational complexity of the proposed DPD is less than the DL DPD.

2.3 Proposed DPD for Multi-Band PAs

In order to accommodate the growing demands of massive applications, the 5G and beyond 5G communication systems must evolve to support multiple standards at the same time. A diversity of wireless standards, along with the application of carrier aggregation (CA), present rigorous requirements for wireless transmitters. The increasing system complexity and fabrication cost are unaffordable and practically impossible. The concurrent multi-band transmitter is one of the most promising solutions to this problem. Since multiple signals in different frequency bands are combined and transmitted in the same nonlinear transmit path, the interaction of concurrent signals will produce complicated nonlinear distortions. In this case, numerous DPD techniques have been developed for multi-band transmitters^[13-15].

The proposed digital predistortion can also be applied in multi-band scenarios. Take dual-band transmitter as an example. The input waveform is composed of dual-band signals, as in Eq. (7).

$$x(n) = x_1(n)e^{-j\omega n T_s} + x_2(n)e^{j\omega n T_s}, \quad (7)$$

where ω is the angular frequency, T_s is the sampling interval of base band signal, and $x_1(n)$ and $x_2(n)$ are the baseband envelop signals at the lower band and upper band respectively. The nonlinear behavior of dual-band PA can still be expressed as:

$$y(n) = \sum_{k=1}^K \sum_{m=0}^{M-1} \alpha_{km} x(n-m) |x(n-m)|^{k-1}. \quad (8)$$

By substituting Eq. (7) into Eq. (8), it is obviously that the output signals at lower band and upper band are related to the input information in each band, and the input signal from the other band also contributes to the distortion. This behavior can be described using 2D-DPD model^[13], as in Eq. (9).

$$\begin{aligned} y_1(n) &= \sum_{m=0}^{M-1} \sum_{k=0}^K \sum_{l=0}^k \beta_{klm}^1 x_1(n-m) |x_1(n-m)|^{k-l} |x_2(n-m)|^l \\ y_2(n) &= \sum_{m=0}^{M-1} \sum_{k=0}^K \sum_{l=0}^k \beta_{klm}^2 x_2(n-m) |x_2(n-m)|^{k-l} |x_1(n-m)|^l, \end{aligned} \quad (9)$$

where $y_1(n)$ and $y_2(n)$ are the output signals at the lower band and upper band respectively. β_{klm}^1 and β_{klm}^2 denote the model coefficients.

The ideal output signals at lower and upper bands are linearized versions which only contain the input information in each band. Therefore, the negative feedback iteration format for dual-band PA has the similar form with that for single band scenario, as in Eq. (10).

$$\begin{aligned} \mathbf{x}_1^{DPD(k)} &= \mathbf{x}_1^{DPD(k-1)} + w_1(\mathbf{u}_1 - \lambda_1 \mathbf{y}_1^{(k)}) \\ \mathbf{x}_2^{DPD(k)} &= \mathbf{x}_2^{DPD(k-1)} + w_2(\mathbf{u}_2 - \lambda_2 \mathbf{y}_2^{(k)}). \end{aligned} \quad (10)$$

Generally, in order to save the fabrication cost, the shared feedback path is adopted to observe the output information in both frequency bands. In this case, the negative feedback iteration is performed on the lower band and upper band by turns. For instance, when identifying the optimal DPD signal for the upper band, the input signal in the upper band is modified in each iteration while the input signal in the lower band remains the same. **Fig. 4** shows the block diagram of the proposed DPD applied in dual-band transmitters.

After estimating the optimal DPD signal in both transmit bands, the predistorters can be identified by forward modeling using the 2D-DPD model in Eq. (9). In this case, the optimal DPD signals $x_1^{DPD}(n)$ and $x_2^{DPD}(n)$ in each band are regarded as the model output, and the original input signals $u_1(n)$ and $u_2(n)$ are the model input. Eq. (11) describes the coefficients extraction using LS algorithm.

$$\begin{aligned} \boldsymbol{\beta}_1 &= (\mathbf{A}_1^H \mathbf{A}_1)^{-1} \mathbf{A}_1^H \mathbf{x}_1^{DPD} \\ \boldsymbol{\beta}_2 &= (\mathbf{A}_2^H \mathbf{A}_2)^{-1} \mathbf{A}_2^H \mathbf{x}_2^{DPD}, \end{aligned} \quad (11)$$

where $\boldsymbol{\beta}_1$ and $\boldsymbol{\beta}_2$ are the coefficients of predistorters in upper and lower frequency band; \mathbf{A}_1 and \mathbf{A}_2 are the basis function matrixes composed of $u_1(n)$ and $u_2(n)$, as in Eq. (9).

3 Experimental Results

In this section, we present experimental results on two broadband DPAs to validate the proposed DPD technique in both single-band and dual-band scenarios. Both PAs are driven in high-efficiency points near the saturation region in order to validate the proposed method's performance and robustness under deep compression.

The experimental setups are depicted in **Fig. 5a**. Within the transmitting chain, a two-channel-synchronized vector sig-

nal generator (R&S SMW200A) was used to generate the broadband and dual-band RF signals from baseband samples. In the dual-band test, a wideband RF power combiner was responsible for combining the multiple signals before feeding them to the driver amplifier and the PA. In the single-band test, an LTE signal stream with a 200 MHz bandwidth (2-carrier) at 2.1 GHz and a 7.5 dB PAPR after crest factor reduction (CFR) were used as inputs in the experimental evaluations. The measurements were applied to a broadband (1.7 GHz – 2.8 GHz) Lab-made Cree CGH40010p DPA. In the dual-band scenario, the evaluations were performed on a Lab-made Cree CGH40010p DPA which was designed for 5G applications

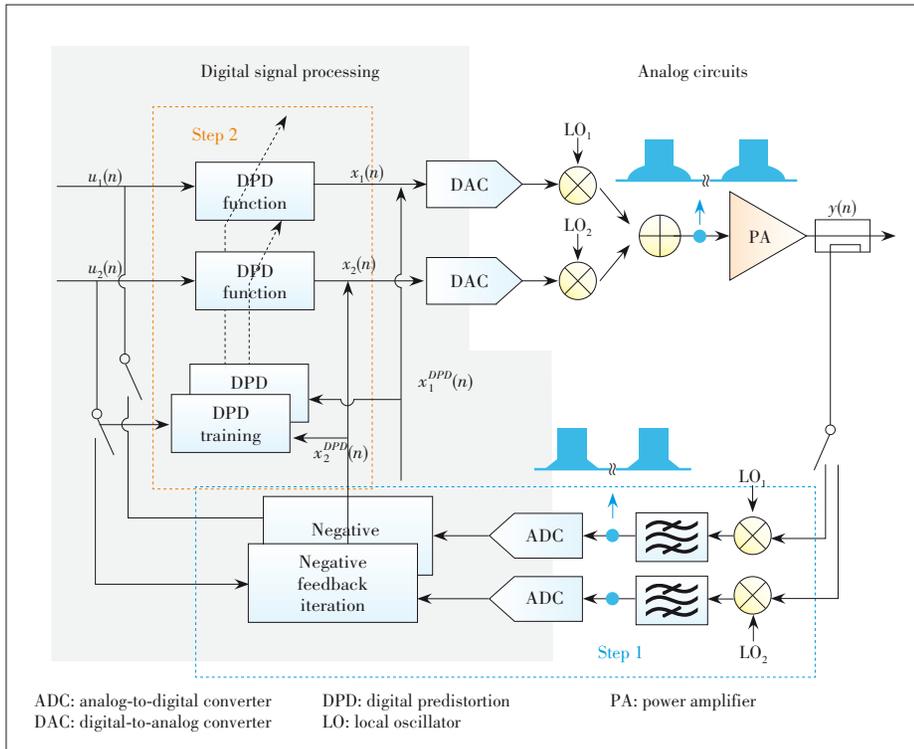
with a bandwidth of 3.3 – 3.8 GHz. The test signals were two 7.5 dB PAPR uncorrelated LTE signals of 10 MHz bandwidth at carrier frequencies of 3.4 GHz and 3.6 GHz. Both the DPAs were operated in the saturation region to acquire high efficiency and obvious nonlinearity for the validation of the proposed DPD. **Figs. 5b** and **5c** show the schematic of Lab-made DPAs.

On the feedback side, the broad and dual-band signals were coupled out from the PA output and thereafter converted to baseband samples by a spectrum analyzer (R&S FSW26). In the dual-band test, the upper band and lower band signals were captured by the wideband feedback path in each time slot, by turns. All algorithms and instrument control operations were performed on the host personal computer (PC) running Matlab. Adjacent channel power ratio (ACPR) was used to evaluate the nonlinear distortions performance.

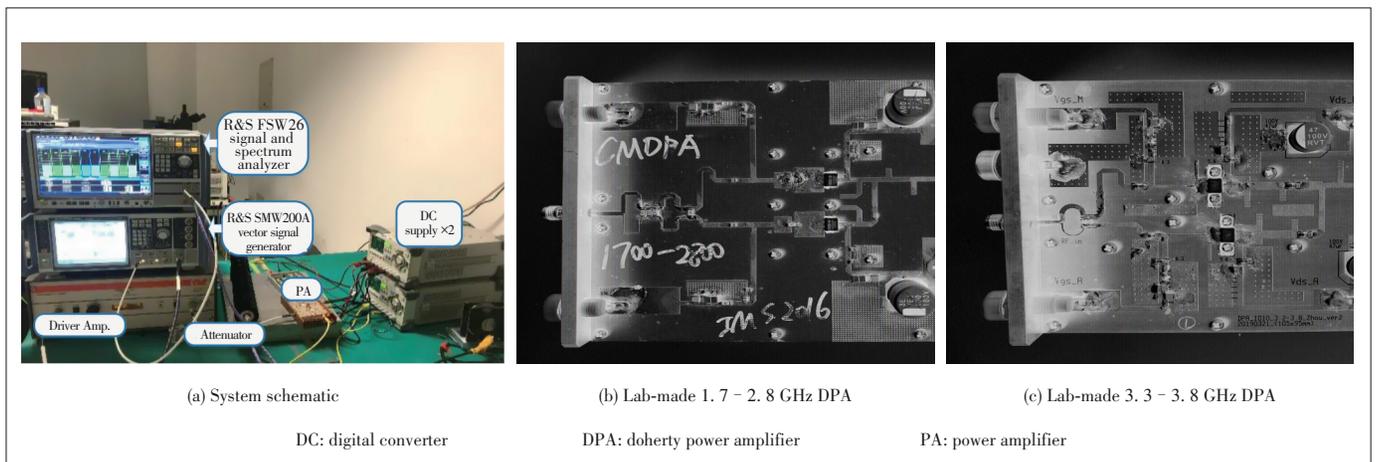
3.1 Evaluations on Broadband PA

In the DPD test, the conventional DL DPD and IDL DPD were performed as well as the proposed DPD for comparison. The feedback depth λ and iteration step w were equal to 1 and 0.3 respectively. When the negative feedback iteration is converged, the output signal of PA is greatly linearized, presenting with the ACPRs of the first adjacent channel approaching -49 dBc.

The parameters of DPD module were estimated utilizing GMP model with $K_a = K_b = K_c = 11$, $M_a = M_b = M_c = 8$ and $L_a = L_b = 6$. **Fig. 6a** shows the AM/AM and AM/PM curve with/without the proposed DPD. The nonlinear distortion, especially the



▲ Figure 4. Structure of the negative feedback iteration based DPD technique in dual-band scenario.



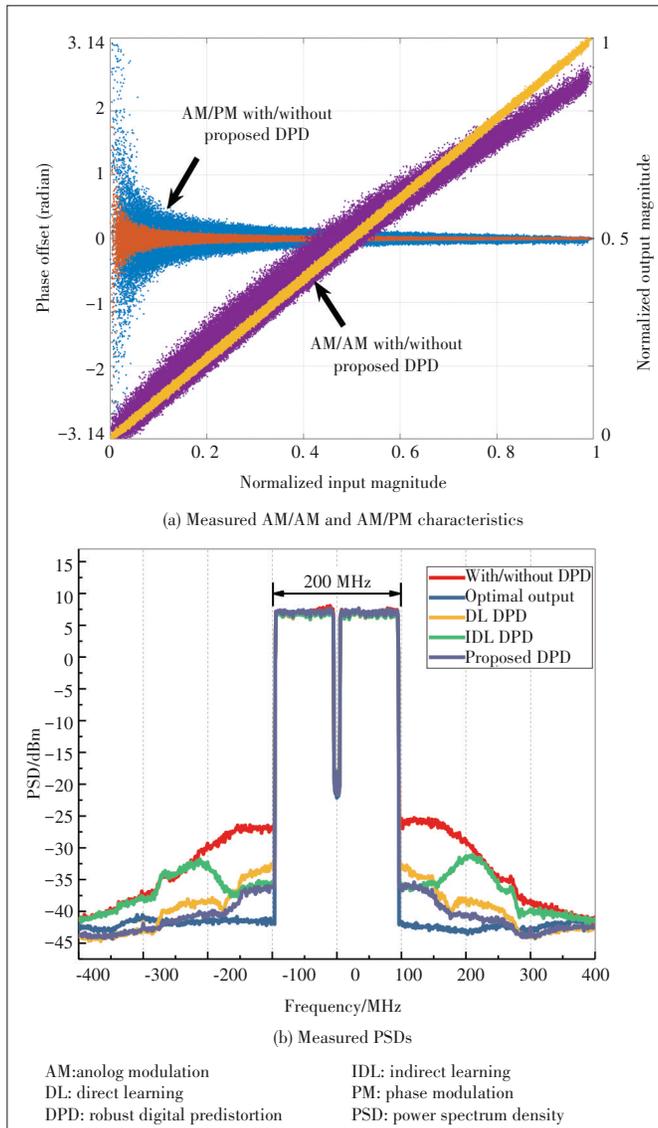
▲ Figure 5. Robust digital predistortion (DPD) test bench.

memory effect, is obvious in the 200 MHz DPD test; however, the nonlinear characteristic has been improved significantly when applying the proposed DPD. **Fig. 6b** presents the power spectrum density (PSD) with/without DPDs at the output of PA. With the proposed DPD, the output signal can achieve -45 dBc ACPR, which outperforms the DL DPD and IDL DPD by 1 dB and 4 dB respectively. **Table 1** summarizes the linear performance of the PA's output signals.

Fig. 7a compares the converging speed between the negative feedback iteration and DL DPD by calculating the normal-

ized mean square error (NMSE) between the PA input and output signals after each iteration. Both the negative feedback iteration and DL DPD converge after 5 - 6 iterations, while the negative feedback method shows a better NMSE performance.

Fig. 7b shows the iteration speed and accuracy with different iteration steps. The converging speed increases with the larger steps, however, the optimal linear performance is getting poorer with the increasing of iteration steps. Furthermore, the linearity of the output signal even becomes worse after the NMSE in the iteration reaches the optimum. The measured results indicate that the iteration step should be appropriately selected to balance the convergence speed and the linear performance.

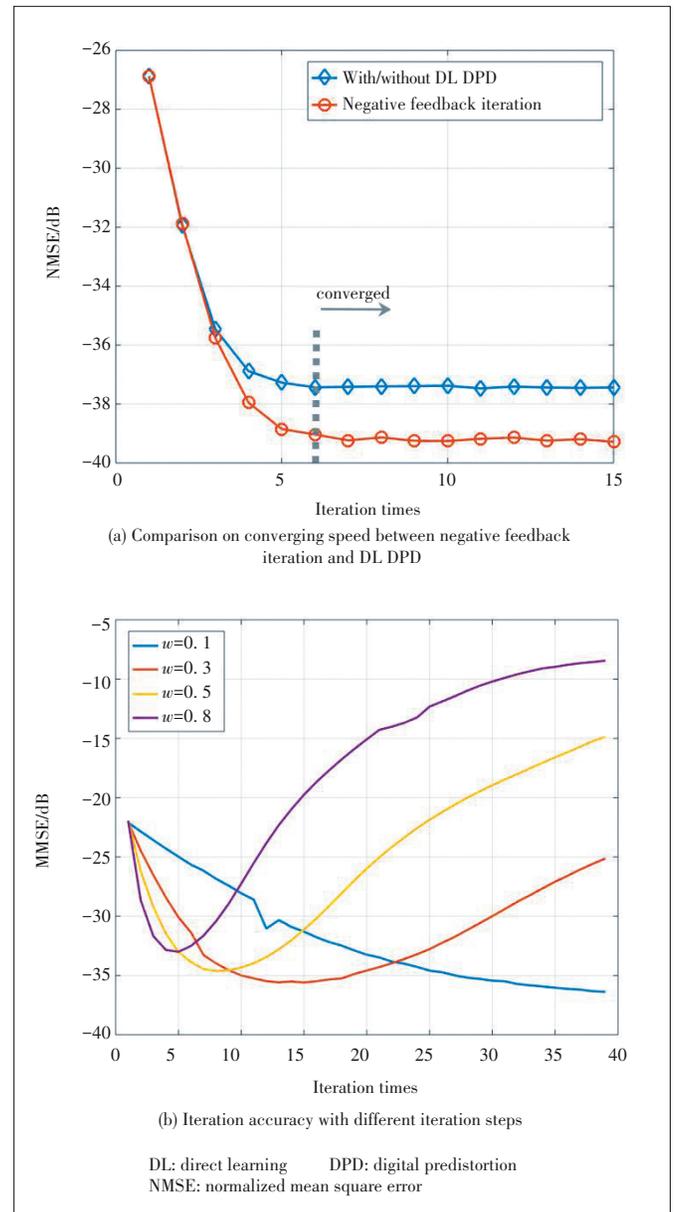


▲ **Figure 6.** Measured AM/AM and AM/PM characteristics and PSDs.

▼ **Table 1.** Measured performance in single band scenario

Scenario	Without DPD	Proposed DPD	DL DPD	IDL DPD
ACPR/dBc (±100 MHz)	-33.31/-34.42	-45.26/-45.25	-44.06/-44.37	-41.48/-42.41

ACPR: adjacent channel power ratio
DPD: digital predistortion
DL: direct learning
IDL: indirect learning

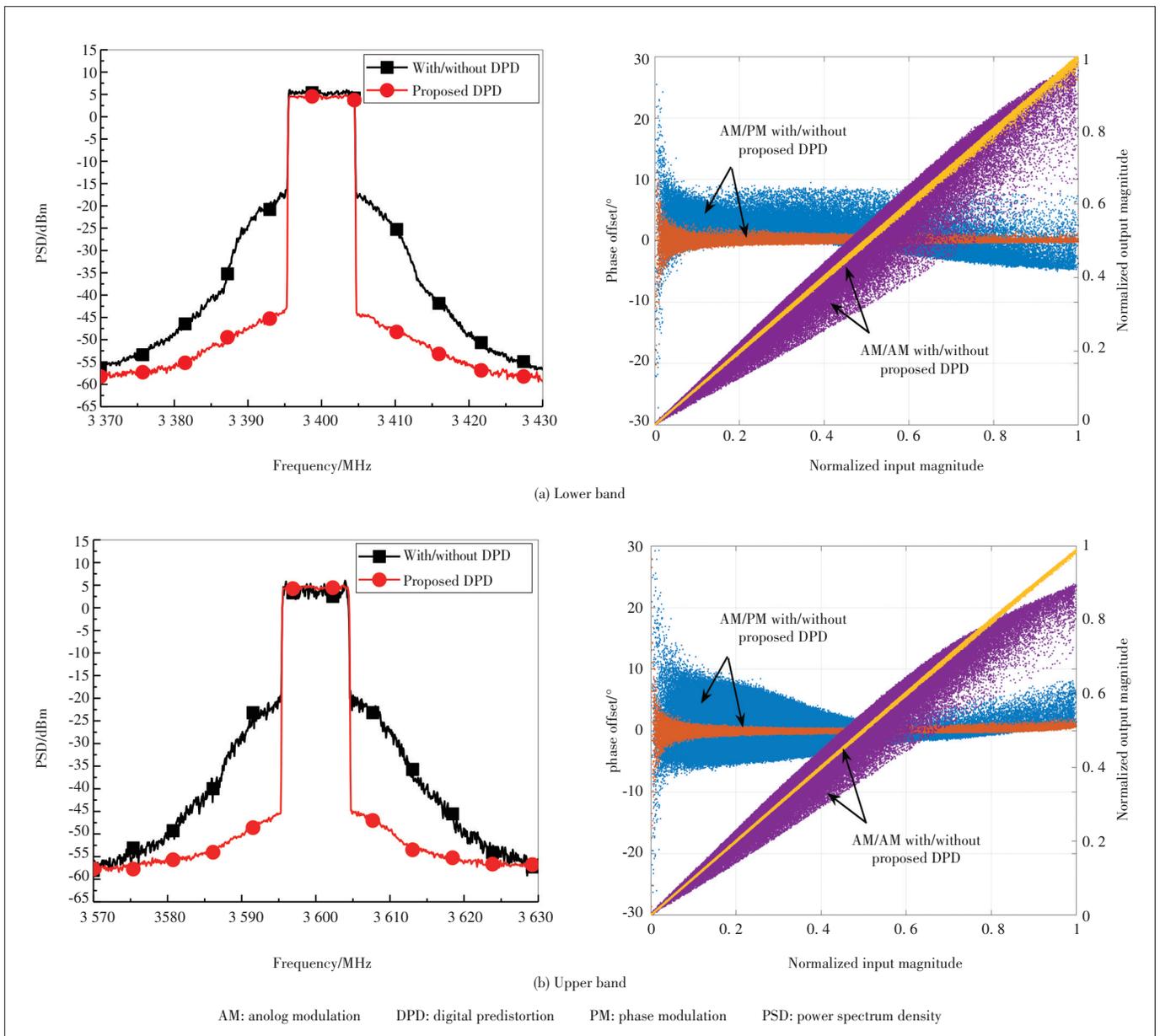


▲ **Figure 7.** Iterative convergence trend.

3.2 Evaluations on Dual-Band PA

The proposed DPD is validated on a broadband (3.3 GHz – 3.8 GHz) DPA with the dual-band input signal. The dual-band signal is separated by 200 MHz at the carrier frequencies of 3.4 GHz and 3.6 GHz. Two uncorrelated 10 MHz LTE signals are applied in the dual-band measurements. The feedback depth λ_1 , λ_2 and iteration steps w_1 , w_2 are the same for both frequency bands, which are equal to 1 and 0.3 respectively. Similar with the single band test, the negative feedback iterations converge quickly after 5 – 6 times modification. When the iteration converges, the optimal DPD signals which improve the ACPRs of PA output signals at both bands to about –55 dBc are obtained.

The parameters of predistorters in lower and upper frequency bands are extracted utilizing 2D-DPD model with $K = 7$, and $M = 4$. **Fig. 8** shows the AM/AM and AM/PM characteristics with/without the proposed DPD. The AM/AM and AM/PM curves in Fig. 8 show notable dispersion, which can be attributed to the intermodulation of the two uncorrelated signals at each frequency band. The nonlinear distortions and intermodulations are compensated significantly with the proposed DPD, showing a more than 20 dB ACPR improvement at both frequency bands. Fig. 8 depicts the observed PSDs of PA output signals at the lower band and upper band. **Table 2** summarizes the above linear performance.



▲ **Figure 8.** Measured PSDs and AM/AM, AM/PM characteristics at power amplifier (PA)'s output with/without the proposed DPD.

▼Table 2. Measured performance in dual-band scenario

Scenario	Lower Band		Upper Band	
	Without DPD	Proposed DPD	Without DPD	Proposed DPD
ACPR/dBc (± 10 MHz)	-28.28/-28.81	-51.71/-51.45	-30.26/-29.43	-54.04/-53.33

ACPR: Adjacent channel power ratio DPD: digital predistortion

4 Conclusions

In this paper, a negative feedback iteration based DPD technique is proposed for linearizing power amplifiers in LTE/5G broadband and multi-band applications. The proposed DPD technique divides the conventional DPD process into two steps, which estimate the optimal DPD signal by negative feedback iteration and then identify the predistorter by forward modeling. Benefited from the iteration, the proposed DPD can achieve a better linearization performance than conventional DL DPD while having a lower computational complexity. The validations are carried on a broadband DPA with a 2-carrier 200 MHz bandwidth LTE signal at 2.1 GHz, and on a dual-band scenario with two 10 MHz LTE signals at 3.4 GHz and 3.6 GHz. The measurements provide potential application value of the proposed DPD in LTE/5G systems.

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