Simplified Dynamic Deviation Reduction-based Volterra Model for Doherty Power Amplifiers

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***Abstract*—A simplified 2nd-order dynamic deviation reduction-based Volterra series model is proposed for characterizing wideband multi-carrier Doherty power amplifiers. By removing several redundant terms, this model has much less complexity but maintains excellent modeling performance, compared to the full-size model. Experimental results show that both nonlinear distortion and memory effects in the Doherty PA can be almost completely removed by employing digital predistortion with proposed model, when excited by 2- and 4-carrier WCDMA signals.**

Keywords- behavioral model; digital predistortion; Doherty; power amplifier; Volterra series.

I. INTRODUCTION

The Doherty amplifier has attracted a great deal of attention in recent years [1][2] because of its high efficiency performance, relative simplicity of implementations and ease of meeting the linearity and bandwidth specifications of current wireless communication systems. However, in a Doherty PA, two (or more) amplifiers are employed and they are typically biased at different bias points – for instance, Class-AB for the main amplifier and Class-C for the auxiliary amplifier. The auxiliary amplifier is only turned on while the main amplifier is saturating. The two amplifiers exhibit very different behavior, which causes the overall linearity of the PA to vary significantly over different input signal power levels. When transmitting wideband signals, such as multi-carrier WCDMA signals, the Doherty PA suffers from strong nonlinear memory effects, and these memory effects exhibit discontinuities due to envelope dependent signal routing over the branch amplifiers.

For the purpose of improving system performance, it is necessary to employ digital predistortion (DPD) techniques to remove nonlinear distortion in the Doherty PA. One of main challenges in developing effective DPD techniques is to find a way to capture accurately the nonlinear distortion and memory effects in the PA using a simple behavioral model. Although much effort has been expended to characterize the Doherty PA [3], most models only work for the case of low memory effects and even then with limited performance. In this paper, we propose an efficient behavioral model for the accurate characterization of the nonlinear behavior of Doherty PAs. This model is derived from the 2nd-order dynamic deviation reduction-based Volterra series but with further simplifications. Experimental results show that the proposed model is a very good compromise between achieving reduced model complexity and maintaining excellent modeling performance.

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II. THE SIMPLIFIED 2ND-ORDER DDR MODEL

To overcome the complexity of the general Volterra series, an effective model-order reduction method, called dynamic deviation reduction (DDR), was proposed in [4]. This is based on the fact that the effects of dynamics tend to fade with increasing order in many real PAs, so that the high-order dynamics can be removed in the model, leading to a significant simplification in model complexity. The 1st-order dynamic truncation of the DDR-based baseband Volterra model in the discrete time can be written as

$$\begin{aligned}\tilde{u}(n) = &\sum_{k=0}^{\frac{P-1}{2}} \sum_{i=0}^{M} \tilde{g}_{2k+1,1}(i) \left|\tilde{x}(n)\right|^{2k} \tilde{x}(n-i) \\ &+\sum_{k=1}^{\frac{P-1}{2}} \sum_{i=1}^{M} \tilde{g}_{2k+1,2}(i) \left|\tilde{x}(n)\right|^{2(k-1)} \tilde{x}^{2}(n)\tilde{x}^{*}(n-i)\end{aligned} \quad (1)$$

where $\tilde{x}(n)$ and $\tilde{u}(n)$ are the complex envelopes of the input and output of the PA, respectively, and $\tilde{g}_{2k+1,j}(\cdot)$ is the complex Volterra kernel of the system. Symbol $(\cdot)^*$ represents the complex conjugate operation and $|\cdot|$ returns the magnitude. Only odd-order nonlinearities are included in (1), i.e., P is an odd number, because the effects from even order kernels can be omitted in a band-limited modulation system.

Experimental results have demonstrated that this 1st-order DDR model can produce excellent performance using only a very small number of parameters when linearizing power amplifiers [5] [6]. These tests were based on a single Class-AB PA, excited with relatively narrowband single carrier WCDMA signals, where only small or moderate memory effects appeared. In these cases, the 1st-order dynamic truncation is adequate since the higher-order dynamics do not significantly affect system performance. However, in a wideband Doherty PA, since strong nonlinear memory effects often appear, the 1st-order truncated DDR model is no longer sufficiently accurate. The straightforward solution would be to include higher-order

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dynamics in the model. For example, the 2nd-order DDR model can be written as

$$\begin{aligned}\tilde{u}(n) &= \sum_{k=0}^{\frac{P-1}{2}}\sum_{i=0}^{M}\tilde{g}_{2k+1,1}(i)\left|\tilde{x}(n)\right|^{2k}\tilde{x}(n-i) \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i=1}^{M}\tilde{g}_{2k+1,2}(i)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}^{2}(n)\tilde{x}^{*}(n-i) \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i_1=1}^{M}\sum_{i_2=i_1}^{M}\tilde{g}_{2k+1,3}(i_1,i_2)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}^{*}(n)\tilde{x}(n-i_1)\tilde{x}(n-i_2) \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i_1=1}^{M}\sum_{i_2=1}^{M}\tilde{g}_{2k+1,4}(i_1,i_2)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}(n)\tilde{x}^{*}(n-i_1)\tilde{x}(n-i_2) \\ &+\sum_{k=2}^{\frac{P-1}{2}}\sum_{i_1=1}^{M}\sum_{i_2=i_1}^{M}\tilde{g}_{2k+1,5}(i_1,i_2)\left|\tilde{x}(n)\right|^{2(k-2)}\tilde{x}^{3}(n)\tilde{x}^{*}(n-i_1)\tilde{x}^{*}(n-i_2)\end{aligned} \quad (2)$$

This 2nd-order model can significantly enhance the memory effect modeling capability, and it has been successfully used for modeling and linearization purposes [7]. However, although it is a simplified version of the full Volterra series, the 2nd-order DDR model still suffers from problems of high complexity in real-world implementation. For example, if we choose a nonlinear order P = 7, and a memory length M = 4, the total number of coefficients will reach 130. A large number of coefficients not only increases the implementation complexity but often also increases model extraction errors since a large matrix must be used to solve the optimization equations. Further pruning of the model must therefore be considered.

As discussed in [5][8], in a real amplifier, nonlinearities or arise from various sources, such as, trapping effects, thermal effects, memory effects induced by bias and matching networks, etc. These nonlinearities affect the output of the PA in different ways and with various degrees. When modeling or compensating for these nonlinearities, it is not necessary to treat them equally; certain terms in the model can be removed without significantly affecting overall performance. In (2), we can see that the 2nd-order dynamics are represented by the last three terms. In the low-pass equivalent format, depending on where the conjugates are applied, these terms can be interpreted as the dynamics resulting from positive second harmonics (+2ω), DC and negative second harmonics (-2ω), respectively, where ω is the center carrier frequency. The last term in (2), which results from -2ω, only has an effect when the nonlinear order P is equal to or greater than five. Given that in a real system, the out of band distortions are mainly generated from the 3rd- and 5th-order nonlinearities, this means that this -2ω term will have very little effect on the output of the PA, and thus can be removed. It was demonstrated in [5] that if we assume the frequency response of the matching networks is flat in the first-zone, then the 2nd -order dynamics can be treated as resulting from the 2nd-order static nonlinearities passing through a linear feedback filter, and then being modulated with other harmonics and falling back to the first zone again. This leads to the conclusion that the index i_1 can be made equal to i_2 in the 2nd-order dynamic terms. After these considerations, the new simplified model can be written as

$$\begin{aligned}\tilde{u}(n) &= \sum_{k=0}^{\frac{P-1}{2}}\sum_{i=0}^{M}\tilde{g}_{2k+1,1}(i)\left|\tilde{x}(n)\right|^{2k}\tilde{x}(n-i) \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i=1}^{M}\tilde{g}_{2k+1,2}(i)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}^{2}(n)\tilde{x}^{*}(n-i) \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i=1}^{M}\tilde{g}_{2k+1,3}(i)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}(n)\left|\tilde{x}(n-i)\right|^{2} \\ &+\sum_{k=1}^{\frac{P-1}{2}}\sum_{i=1}^{M}\tilde{g}_{2k+1,4}(i)\left|\tilde{x}(n)\right|^{2(k-1)}\tilde{x}^{*}(n)\tilde{x}^{2}(n-i)\end{aligned} \quad (3)$$

This new model contains all static and the 1st-order dynamic terms, but only includes some essential terms from the 2nd-order dynamics. Compared to the full 2nd-order DDR model (2), where 2-dimensional convolution is involved, only 1-dimensional convolution is required in (3). The complexity of the model is therefore dramatically reduced. For example, the number of coefficients is reduced to 56 when P = 7 and M = 4.

III. Experimental Results

In order to validate the proposed model, we tested a LDMOS Doherty PA operated at 1.9 GHz and excited by multi-carrier WCDMA signals with average output power at 47 dBm and with 6.3 dB PAPR. The test bench set-up was similar to that in [4]. A total of 92,160 I/Q samples were captured at the input and output of the PA with a data rate at 92.16 M samples/second. Of these, 4,000 samples were used for model extraction employing the Least Squares (LS) algorithm, while the remainder of the data was used for model validation in separate measurements. Different nonlinear orders and memory lengths were chosen to assess model accuracy. For comparison, we also implemented the other two models: the 1st-oder DDR model in (1), and the full 2nd-order DDR model in (2), which are represented as Model S1 and Model S2 respectively in the following results and plots. The new simplified 2nd-order DDR model as shown in (3) is called Model S3.

A. *Model Accuracy Evaluation*

Two assessments were considered to evaluate the performance of the new model: NMSE (Normalized Mean Square Error) in the time domain and EPSD (Error Power Spectral Density) in the frequency domain.

The NMSE results are shown in Table I, and the EPSD plots along with the original PA output spectra for the 2-carrier and 4-carriers signals are shown in Fig.1 and Fig.2, respectively, where we can see that significant improvements were obtained by using the 2nd-order DDR models. There is almost no difference between the results produced by the two 2nd-order models (full size one and simplified one); however, the simplified 2nd-order model requires a much smaller number of coefficients, especially when higher order nonlinearity and longer memory length are involved, compared to the full-size model. This indicates that the simplified model maintains almost the same accuracy of the full-size model but with much lower complexity.

TABLE I. NMSE COMPARISON OF DIFFERENT MODELS

Model		P=7; M=2		P=7; M=4		P=15; M=2		P=15; M=4	
		NMSE (dB)	*No. coef*[3]	*NMSE (dB)*	*No. coef*	*NMSE (dB)*	*No. coef*	*NMSE (dB)*	*No. coef*
S1	2c[1]	-38.2	18	-38.4	32	-39.3	38	-39.5	68
	4c[2]	-37.4		-38.2		-38.1		-38.9	
S2	2c	-40.9	45	-41.7	130	-43.3	105	-44.6	310
	4c	-38.7		-40.3		-39.7		-41.7	
S3	2c	-40.7	30	-41.6	56	-43.1	66	-44.7	124
	4c	-38.6		-40.3		-39.5		-41.8	

1. 2c: 2-carrier; 2. 4c: 4-carrier; 3. No coef: Number of coefficients.

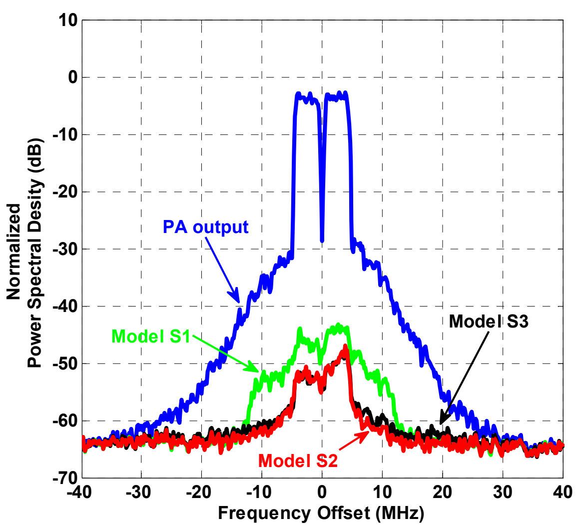

Fig. 1 EPSD plots for 2-carrier signals: $P = 15$, $M = 4$.

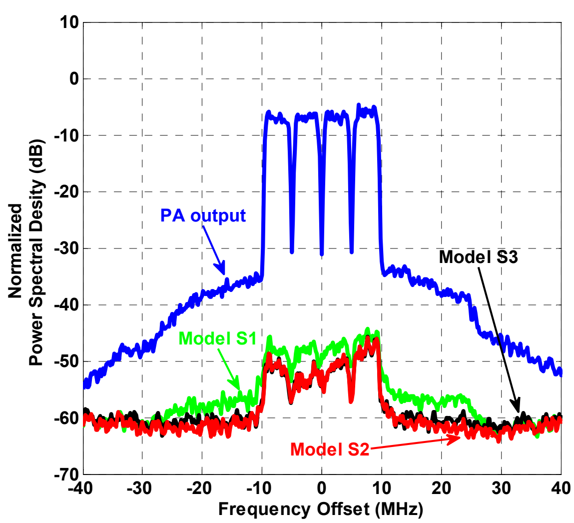

Fig. 2 EPSD plots for 4-carrier signals: $P = 15$, $M = 4$.

B. *Predistortion Performance Accessment*

In the second test, we intend to evaluate the new simplified Volterra model for the purpose of digital predistortion (DPD). Since the AM/AM curve of the PA is a kind of "S" shape as shown in Fig.3, which is difficult to linearize by using a single Volterra function, in this test, we employed the vector threshold decomposition technique proposed in [6], along with the new simplified 2nd-order DDR model, to conduct the digital predistortion for the high power Doherty PA. More than 25 dB improvements in ACPRs can be made with this new DPD model both for 2-carrier and 4-carrier WCDMA signals at 47 dBm output power. The AM/AM plot and AM/PM plot are shown in Fig.3 and Fig.4, respectively, and the spectra plots are given in Fig.5 and Fig.6, where we can see that nonlinear distortion and memory effects are effectively removed after DPD.

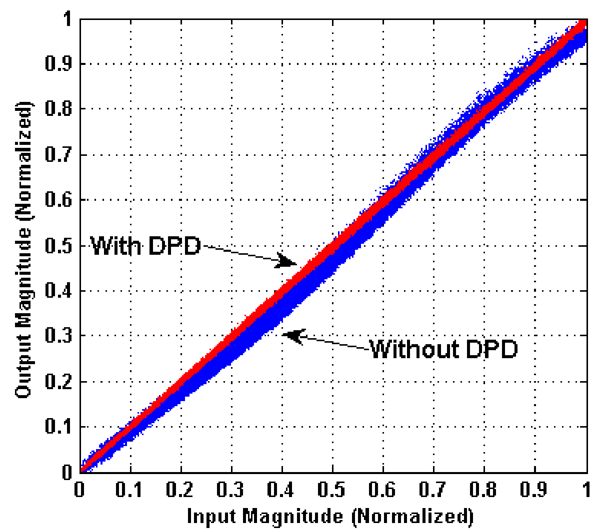

Fig. 3 AM/AM plot for 4-carrier WCDMA signals.

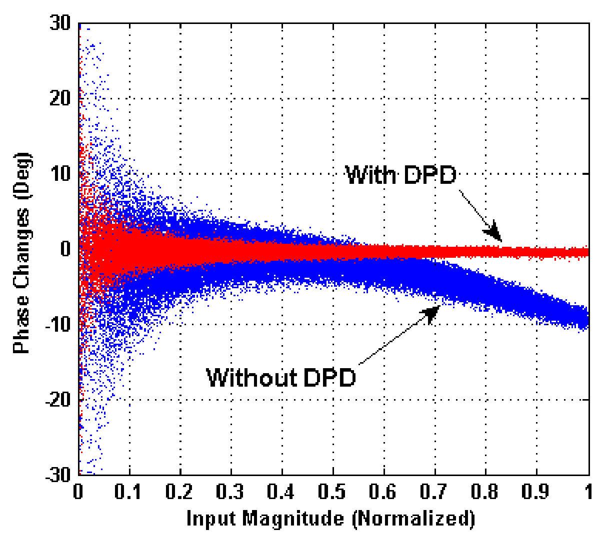

Fig. 4 AM/PM plot for 4-carrier WCDMA signals.

C. *Implementation Complexity Comparison*

Generally, the higher order dynamics involve in the behavioral model, the more hardware cost requires. We intend to achieve a good DPD performance while keep the implementation cost as low as possible. In the sense of physical realizability, a further advantage of the proposed simplified model (S3) lies in the low-cost real hardware implementation. Model S3 has a similar form to Model S1, where only 1-dimensional convolution is involved. This is another original intention for model simplification. As a result, it can be efficiently implemented in hardware with low cost by using LUT (look-up table) assisted gain indexing and time-division multiplexing based multiplier sharing approaches proposed in [9]. For comparison, we implemented the three models with factors P = 7 and M = 4 on a Xilinx Virtex-5 XC5VSX95T chip. The hardware resource utilization is shown in Table II. Clearly, compared to the full-size model (S2), the hardware resource usage of the simplified model (S3) has been dramatically reduced, with savings of more than 60 %.

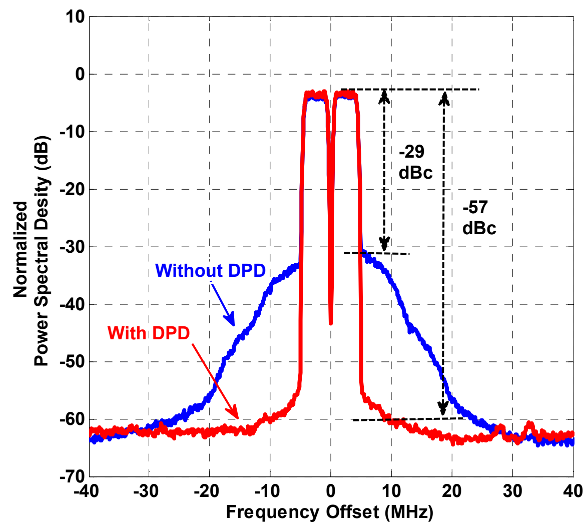

Fig. 5 Output spectra for 2-carrier WCDMA signals with and without DPD.

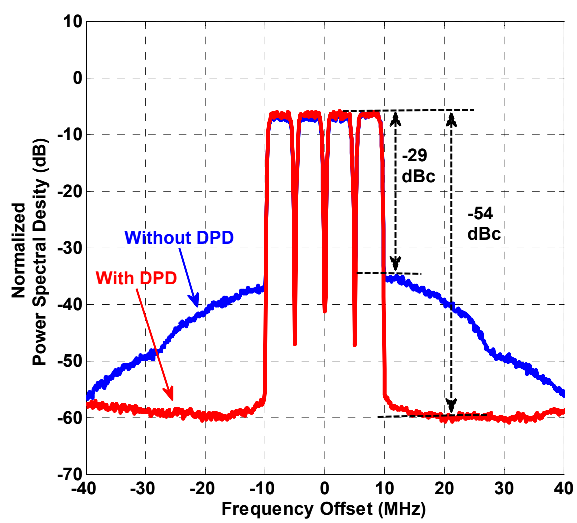

Fig. 6 Output spectra for 4-carrier WCDMA signals with and without DPD.

TABLE II. FPGA RESOURCE UTILIZATION COMPARISON

Model	Types of Resource			
	DSP48Es	***Slice Register***	***Slice LUTs***	***Block RAM***
Total[1]	640	58880	58880	244
S1	16 (2.5%)	1387 (2.4%)	1356 (2.3%)	9 (3.7%)
S2	160 (25.0%)	6091 (10.3%)	5328 (9.0%)	57 (23.4%)
S3	40 (6.3%)	2171 (3.7%)	2018 (3.4%)	17 (7.0%)

1. Based on the hardware resource of Xilinx Virtex-5 XC5VSX95T chip.

IV. Conclusion

In this paper, we have proposed a simplified 2nd-order dynamic deviation reduction-based Volterra model. This model can accurately characterize the nonlinear behavior and memory effects of multi-carrier Doherty power amplifiers, and thus can be used to effectively compensate for the distortion induced by the Doherty PA in digital predistortion. Though compared to the 1st order DDR model, more parameters are involved in the proposed simplified 2nd order DDR model, compared to the full size 2nd order DDR model, this proposed model uses a much smaller number of parameters and requires much less hardware resources but still maintains excellent performance.

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