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A Low-Complexity Dual-Band Model for Dual-band Power Amplifiers Based on Volterra Series

Tianjing Zhang*, Cuiping Yu, Yuanan Liu, Shulan Li, and Bihua Tang

Abstract—A novel low-complexity dual-band memory polynomial (2D-LCMP) model for linearization of dual-band power amplifiers (PAs) is proposed in this paper. The in-band intermodulation (IM) and cross-band modulation (CM) distortion terms in the prior two-dimensional models have different impacts on the model performance. Therefore, they are considered respectively in the proposed model. Some redundant distortion terms are removed away to decrease the model complexity. In addition, the nonlinearity order and memory depth are frequency dependent for each band. Experimental measurements were performed on two types of wideband PAs. The results prove the superiority of the 2D-LCMP model.

1. INTRODUCTION

With the development of modern wireless communication systems, supporting multi-standard signals simultaneously in one communication system is an inevitable trend. Therefore, the power amplifier (PA), one of the uppermost components in the radio frequency transmitters, ought to support signals in different frequency bands concurrently. Intensive research has been carried out for concurrent dual-band PA including its design techniques and nonlinear compensation techniques.

Traditional single-band digital predistortion (DPD) techniques [1–9] fail to compensate nonlinear distortion of dual-band PAs. On the one hand, the sampling rate requirements for hardware facilities, the analog-to-digital converter (ADC) and the digital-to-analog converter (DAC), is impractical when the output signal of dual-band PA is sampled as a full band signal. On the other hand, only the IM distortion terms are considered when using single-band DPD techniques for each band independently.

In order to solve this problem effectively, some concurrent dual-band DPD techniques have been proposed in previous works. In [10], a two-dimensional digital predistortion (2D-DPD) model was applied in the dual-band PA's linearization successfully. The main difference between 2D-DPD model and single-band DPD model is that the former further takes CM distortion terms into consideration in addition to the IM distortion terms. What's more, the 2D-DPD model compensates nonlinear distortion in different frequency bands separately. The 2D-DPD model suffers from the shortcoming of high computational complexity. Three summations are required and the total number of coefficients is very large in 2D-DPD model. Authors in [11] proposed a simplified dual-band model based on the 2D-DPD model and outstanding model performances are achieved with low-complexity. However, the application of this model is limited to seventh-order nonlinearity. It becomes complicated and impractical with the increasing of nonlinearity order. A two-dimensional modified memory polynomial (2D-MMP) model was proposed in [12], which only contains two summations due to the modification of envelope terms. But an extra envelope coupling factor is added in it compared to single-band memory polynomial (MP) model. The exact value of envelope coupling factor is determined by complicated binary search algorithm.

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* Corresponding author: Tianjing Zhang (zhangtianjing@bupt.edu.cn).
The authors are with the School of Electronic Engineering, Beijing Key Laboratory of Work Safety Intelligent Monitoring, Beijing University of Posts and Telecommunications, P. O. Box 282, Beijing 100876, China.

In this paper, a low-complexity dual-band memory polynomial (2D-LCMP) model for dual-band PAs is proposed. Because some redundant distortion terms are removed away and the nonlinearity order and memory depth are frequency dependent, the number of coefficients is largely decreased. It acquires comparable model performance to prior 2D-DPD model and outperforms 2D-MMP model.

2. A LOW-COMPLEXITY DUAL-BAND DIGITAL PREDISTORTION MODEL

2.1. Prior Work

Generally, in concurrent dual-band mode, the discrete time baseband equivalent input signal with the angular frequency separation $\Delta\omega = |\omega_2 - \omega_1|$ can be given by

$$x(n) = x_1(n)e^{j\omega_1 nT} + x_2(n)e^{j\omega_2 nT} \tag{1}$$

where $x_1(n)$ and $x_2(n)$ are the complex envelopes of each band. Simplified versions of Volterra series are commonly used methods for modeling the PA's nonlinear behavior. Among them, MP model is the most popular one. The nonlinear behavior of concurrent dual-band PA can be modeled by seventh-order memoryless MP model

$$y(n) = A_1 x(n) + A_3 x(n)\left|x(n)\right|^2 + A_5 x(n)\left|x(n)\right|^4 + A_7 x(n)\left|x(n)\right|^6 \tag{2}$$

where $x(n)$ and $y(n)$ are the input and output baseband signal, and A_i $(i = 1, 3, 5, 7)$ are the model coefficients. Substituting (1) into (2), the complex baseband output signals around each carrier frequency can be represented as (3)

$$\begin{aligned} y_i =\ & x_i\left(A_1 + A_3\left|x_i\right|^2 + A_5\left|x_i\right|^4 + A_7\left|x_i\right|^6\right) + x_i\left(2A_3\left|x_j\right|^2 + 3A_5\left|x_j\right|^4 + 4A_7\left|x_j\right|^6\right) \\ & + x_i\left(6A_5\left|x_i\right|^2\left|x_j\right|^2 + 18A_7\left|x_i\right|^2\left|x_j\right|^4 + 12A_7\left|x_i\right|^4\left|x_j\right|^2\right) \end{aligned} \tag{3}$$

where $x_i(n)$ and $x_j(n)$ $(i \neq j)$ are replaced by x_i and x_j for simplification, and symbol $|\cdot|$ is the magnitude of the complex envelope signal. The expression illustrates that output signal in each band is related to both input signals. Based on (3), the 2D-DPD model including memory distortion terms is proposed in the form of (4)

$$y_i(n) = \sum_{m_i=0}^{M_i}\sum_{k_i=0}^{K_i}\sum_{l_i=0}^{k_i} c^i_{k_i,m_i,l_i} x_i(n-m_i) \times \left|x_i(n-m_i)\right|^{k_i-l_i}\left|x_j(n-m_i)\right|^{l_i} \quad (i = 1, 2) \tag{4}$$

where $c^i_{k_i,m_i,l_i}$ are the model coefficients, and K_i and M_i are the nonlinearity order and memory depth, respectively.

2.2. Proposed Model

In prior dual-band predistortion models, the nonlinearity order and memory depth always have the same value for input signals around each carrier frequency (in case of 2D-DPD model: $K_1 = K_2$, $M_1 = M_2$). However, some distortion terms have little influence on modeling performance and can be removed away for model simplification. As can be seen from (3), the average powers of CM distortion terms are larger than those of IM distortion terms in equal nonlinearity order when the two input signals have equal bandwidths and powers. For example, the average power of third-order CM distortion terms $(2A_3 x_i|x_j|^2)$ is larger than that of corresponding IM distortion terms $(A_3 x_i|x_i|^2)$. Generally, the distortion terms with larger average powers are more indispensable for nonlinear compensation. Thus, it is easy to conclude that the CM distortion terms are more important than IM distortion terms for same nonlinearity order when the two input signals have equal bandwidths and powers.

Such a criterion cannot be applied to the case of unequal nonlinearity order directly because of the unknown relationships of model coefficients A_i $(i = 1,\ 3,\ 5,\ 7)$ in (2) or the case of unequal bandwidths and powers. Authors in [13] discussed the impacts of IM and CM distortion terms by using baseband simulation and analysis. Based on simulation results in [13], it clearly concludes that CM distortion terms are dominant for signals with narrower bandwidths and lower powers. Conversely, for signals with wider bandwidths and higher powers, IM distortion terms are dominant. These conclusions are obtained from some particular cases, which the ratios between input signals in terms of powers and bandwidths are specific. However, the clear scopes of ratios are hard to define and so these results may not be applied in other cases successfully. Generally, it is difficult to confirm which distortion terms are more important, IM or CM distortion terms. What one can make sure is that their impacts on model performance are different in most cases. Therefore, it is reasonable to take IM and CM distortion terms into consideration individually. Moreover, there is no need to set equal nonlinearity order and memory depth for each band. In order to reduce model computational complexity, a novel low-complexity dual-band memory polynomial (2D-LCMP) model for concurrent dual-band PA is proposed in this paper.

$$\begin{aligned} y_1(n) &= \sum_{m_1=0}^{M_1}\sum_{k_1=0}^{K_1} a_{k_1,m_1} x_1(n-m_1)\left|x_1(n-m_1)\right|^{k_1} \\ &\quad + \sum_{m_2=0}^{M_2}\sum_{k_2=1}^{K_2}\sum_{l_1=1}^{k_2} b_{k_2,m_2,l_1} x_1(n-m_2)\left|x_1(n-m_2)\right|^{k_2-l_1}\left|x_2(n-m_2)\right|^{l_1} \\ y_2(n) &= \sum_{m_3=0}^{M_3}\sum_{k_3=0}^{K_3} c_{k_3,m_3} x_2(n-m_3)\left|x_2(n-m_3)\right|^{k_3} \\ &\quad + \sum_{m_4=0}^{M_4}\sum_{k_4=1}^{K_4}\sum_{l_2=1}^{k_4} d_{k_4,m_4,l_2} x_2(n-m_4)\left|x_2(n-m_4)\right|^{k_4-l_2}\left|x_1(n-m_4)\right|^{l_2} \end{aligned} \tag{5}$$

where (a_{k_1,m_1}, b_{k_2,m_2,l_1}, c_{k_3,m_3}, d_{k_4,m_4,l_2}) are the model coefficients, and K_i and M_i ($i = 1, 2, 3, 4$) are the nonlinearity order and memory depth. Note that parameter settings for each band are related to bandwidths and powers. Thus, it gives more flexibility in characterization of concurrent dual-band PA's nonlinear behavior, and decreases computational complexity. According to (5), the output signals are linear with the coefficients, so least square (LS) algorithm is used for model identification. Because two branches are contained in (5) for each band, a pruning approach [7] is used for identifying each branch parameters separately. In order to demonstrate the fact that some distortion terms are redundant in 2D-DPD model, the maximum nonlinearity order K and memory depth M of the proposed 2D-LCMP model are same with those of 2D-DPD model ($\max(K_i) = K$, $\max(M_i) = M$, $i = 1, 2, 3, 4$) in the following experiments.

3. MODEL VERIFICATION

Measurements were carried out for assessing the performance of the proposed 2D-LCMP model. The experiment setup is the same as that described in [14], which consists of a signal generator (N5182A) as DAC and frequency up-converting unit, a wideband PA, an attenuator, a vector signal analyzer (N9030A) to capture the signals and a computer for signal recording and signal processing.

To verify the effectiveness of the proposed 2D-LCMP model, two types of PAs were used in the experiments. One is a wideband class-F PA, the other is a wideband Doherty PA. In the experiment, the output signals were captured in two steps by setting the central frequency to lower band (LB@2.61 GHz) and upper band (UB@2.69 GHz) respectively. Then the output signals were time aligned with their respective input signals for further signal processing and model identification.

Four different signal scenarios were considered and summarized in Table 1. They are set with variable ratio between occupied bandwidths of signals (BW1 and BW2) and powers (PW1 and PW2). For comparison, the 2D-DPD model with nonlinearity order of seven ($K = 6$) and memory depth of two ($M = 2$) was used. The prior 2D-MMP model with nonlinearity order of nine ($K = 8$) and memory depth of two ($M = 2$) was also employed.

Figure 1 shows the measured spectra of the output signals at LB and UB before and after predistortion of wideband Doherty PA. The results in Figures 1(a) and (b) demonstrate the effectiveness of the proposed model in suppressing the out-of-band distortion of Doherty PA. It is obvious that the proposed model can acquire better linearity performance than prior 2D-MMP model. What's more,

Table 1. Summary of four scenarios.

	LB@2.61 GHz	UB@2.69 GHz	
Scenario I	WCDMA BW1 = 3.84 MHz	WCDMA BW2 = 3.84 MHz	BW1 = BW2 PW1 = PW2
Scenario II	16 QAM BW1 =8.19 MHz	16 QAM BW2 = 4.09 MHz	BW1 = 2BW2 PW1 = 4PW2
Scenario III	WCDMA BW2 = 3.84 MHz	WCDMA BW2 = 3.84 MHz	BW1 = BW2 PW1 = 2PW2
Scenario IV	16 QAM BW1 =8.19 MHz	16 QAM BW2 = 4.09 MHz	BW1 = 2BW2 PW1 = PW2

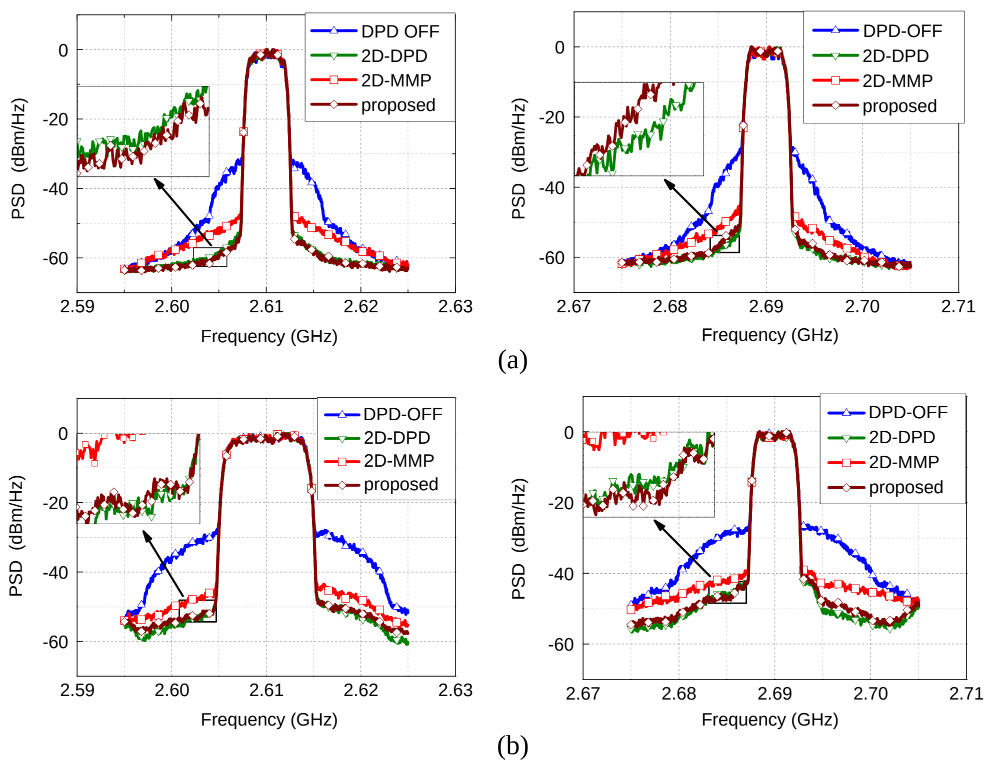

Figure 1. Measured Spectra of the outputs of the wideband Doherty PA. (a) Scenario I (BW1 = BW2 PW1 = PW2). (b) Scenario II (BW1 = 2BW2 PW1 = 4PW2).

the proposed model can realize almost the same linearization accuracy as 2D-DPD model. This is mainly because the unimportant distortion terms are removed away in the 2D-LCMP model compared to 2D-DPD model. Similar measured results are presented in Figures 2(a) and (b) of Class-F PA, which also proved that the proposed 2D-LCMP model and 2D-DPD model achieve better performance in compensating for nonlinearity distortion than 2D-MMP model.

The detailed results of normalized mean square error (NMSE) between the output signals and corresponding input signals are listed in Table 2 and Table 3. The number of coefficients (Coef_num) for model extraction is also presented. It also shows that 2D-LCMP model exhibits almost comparable linearization accuracy as 2D-DPD model for all the scenarios. One can notice that, the proposed 2D-LCMP model requires much less number of coefficients than 2D-DPD model to acquire almost same model accuracy in mitigating in-band distortion of different types of PA. Furthermore, the proposed 2D-LCMP model performs better than 2D-MMP model with comparable computational complexity. In summary, the main advantages of the 2D-LCMP model are low-complexity and excellent model performance.

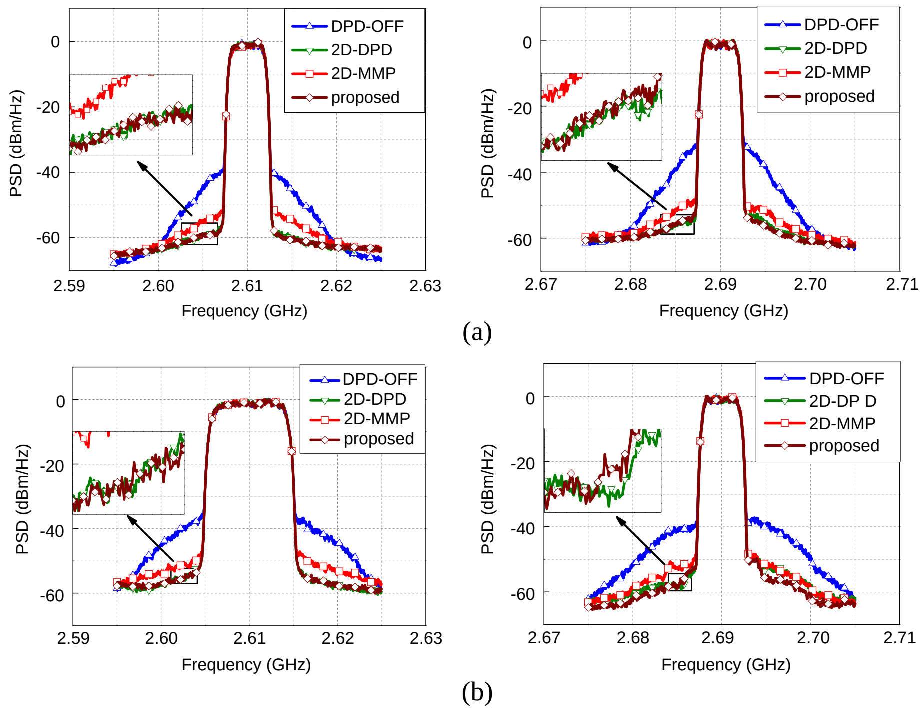

Figure 2. Measured Spectra of the output of the Class-F PA. (a) Scenario III (BW1 = BW2 PW1 = 2PW2). (b) Scenario IV (BW1 = 2BW2 PW1 = PW2).

Table 2. Comparisons of NMSEs and the number of coefficients for Doherty PA.

Model	Scenario I		Scenario II	
	NMSE at LB/UB(dB)	Coef_num	NMSE at LB/UB (dB)	Coef_num
DPD-OFF	-/-	-	-/-	-
2D-DPD	$-39.46/-39.84$	168	$-39.97/-37.93$	168
2D-MMP	$-36.26/-37.21$	54	$-35.53/-32.64$	54
2D-LCMP	$-39.22/-39.63$	72	$-40.25/-37.28$	55

Table 3. Comparisons of NMSEs and the number of coefficients for Class-F PA.

Model	Scenario III		Scenario IV	
	NMSE at LB/UB(dB)	Coef_num	NMSE at LB/UB(dB)	Coef_num
DPD-OFF	-/-	-	-/-	-
2D-DPD	$-45.83/-42.11$	168	$-43.59/-43.21$	168
2D-MMP	$-41.38/-39.65$	54	$-40.77/-41.84$	54
2D-LCMP	$-45.49/-42.36$	56	$-43.75/-43.58$	62

4. CONCLUSIONS

In this paper, a low-complexity concurrent dual-band memory polynomial (2D-LCMP) model based on Volterra series is proposed for compensating nonlinear distortion of dual-band PAs. Measurement results demonstrate the effectiveness and robustness of the proposed 2D-LCMP model for all cases. Since the distortion terms with little contribution to model performances are removed away, the number of coefficients is significantly decreased.

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