A GENERAL BASEBAND VOLTERRA MODEL FOR DUAL-BAND PREDISTORTION

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ABSTRACT

Dual-band and multi-band power amplifiers (PAs) becomes popular as they can effectively reduce the equipment cost and operation cost. On the other hand, the nonlinear interference among signals in different bands needs special attention. Previous modeling results [1] suffer performance degradation when the intermodulation terms among bands fall into bands of the signals. In this paper, we start from the passband Volterra model and derive a general baseband Volterra model considering all possible intermodulation terms. Existing model in [1] is a special case of the proposed baseband Volterra model. Simulation results show that the proposed dual-band Volterra DPD model can provide additional 2 dB performance improvement comparing to the existing dual-band Volterra DPD model.

Index Terms— Nonlinear system modeling, dual-band power amplifier, digital predistortion, Volterra model.

1. INTRODUCTION

Dual-band and multi-band wireless communication systems have become popular in recent years for the advantage of high integration and low cost. Similar to the conventional wireless communication systems, the nonlinearity of the radio frequency (RF) power amplifier (PA) in the dual-band wireless transceivers is the limiting factor of the system performance. The trade off between the power efficiency and linearity needs special attention [2, 3].

In addition to the nonlinear effects such as in-band distortion and out-of-band spectral regrowth as shown in the single-band nonlinear system, the dual-band nonlinear system suffers from the interference among signals in different band [4, 5]. The adaptive digital predistortion (DPD) linearization technology can be applied to the linearization of dual-band PA [6, 7].

The authors in [8] proposed a dual-band memory polynomial model by substituting the dual-band input signal into the memory polynomial model for single-band PA. In [9], the authors analyzed the impact of the model accuracy with the cross-band modulation and proposed a two-dimensional modified memory polynomial model for dual-band PA linearization. However, the above models are obtained by directly applying the single-band baseband PA models to the dual-band scenarios. Such extension is questionable since the baseband models are just mathematical equivalent models of the passband nonlinearity, thus do not contain all information not the actual passband nonlinearity.

In [10], the authors proposed a low-complexity dual-band Volterra-series model for dual-band DPD with enumeration methods. In [1], the authors proposed a baseband equivalent Volterra model with physical constraints. However, the derivation of existing dual-band models assumed that the out-of-band intermodulation products were far from the operating bands and could be easily filtered out [8]. This assumption is appropriate in many dual-band systems. Since existing wireless standards occupies nearly all wireless spectrum, this assumption is not always true. In such cases, the modeling accuracy and the linearization performance can be significantly degraded. In this paper, we start with the physical constraints of the dual-band PA and derive a new dual-band Volterra model. The proposed model puts no constraints on the operating bands. Simulation results show that the proposed dual-band Volterra model can achieve about 2 dB performance improvement over the existing dual-band Volterra model.

The rest of the paper is organized as follows: Section 2 introduces the baseband equivalent Volterra model for dual-band systems. We show the limitation of such model if the cross terms are not properly included. Section 3 proposes a new baseband Volterra model. We show that the model in [1] is a special case of the proposed model. Section 4 validates the effectiveness of the proposed model with simulation. Finally, Section 5 concludes this paper.

2. DUAL-BAND PA AND DPD SYSTEM

For a dual-band PA system, the adaptive dual-band DPD linearization technique is attractive as it offers good compromise between linearization performance and implementation cost [8, 11]. Fig. 1 shows the block diagram of an adaptive

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dual-band PA and DPD system with indirect learning architecture [12]. In Fig. 1, $x_1(n)$ and $x_2(n)$ are the original baseband inputs of band #1 and band #2, respectively; $y_1(n)$ and $y_2(n)$ are the baseband PA outputs of band #1 and band #2, respectively; $z_1(n)$ and $z_2(n)$ are the DPD outputs as well as the PA inputs of band #1 and band #2, respectively.

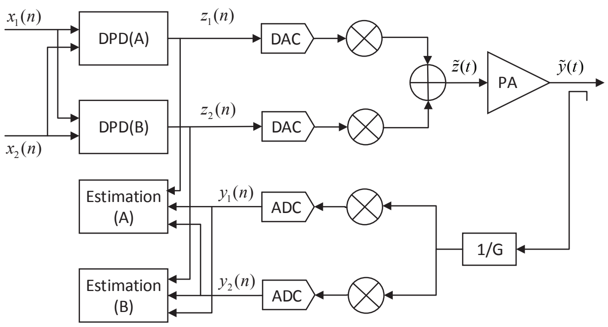


Fig. 1: Block diagrams of an adaptive dual-band DPD system with indirect learning architecture.

The physical behaviour of the dual-band PA in RF domain can be modeled by a Volterra model [10, 13]:

$$\tilde{y}(t) = \sum_{l=1}^{\infty} \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} \tilde{h}_l(\tau_1, \cdots, \tau_l) \cdot \prod_{i=1}^{l} \tilde{z}(t-\tau_i) d\tau_1 d\tau_2 \cdots d\tau_l, \quad (1)$$

where $\tilde{h}_l(\tau_1, \cdots, \tau_l)$ is the l-th Volterra kernel, $\tilde{y}(t)$ and $\tilde{z}(t)$ are RF output and input of the dual-band PA, and

$$\tilde{z}(t) = \mathrm{Re}[z_1(t) \cdot e^{j\omega_{c_1} t} + z_2(t) \cdot e^{j\omega_{c_2} t}]. \quad (2)$$

Substituting (2) into (1), the passband Volterra model can be rewritten as (3).

Since the power amplifier exhibits frequency selectivity, only the frequency components around the carrier frequencies are actually transmitted. In (3), the frequency components are $e^{j[(a-b)\cdot\omega_{c_1} + (a+b+2c-l)\cdot\omega_{c_2}]t}$. By assuming that the out-of-band intermodulation products are far from the dual operating bands and can be easily filtered out, the remaining components around the carrier frequencies can be expressed by a, b, and c.

In [1], the authors provided a physical constraint on the remaining components based on the assumption that the out-of-band intermodulation products are far from the dual operating bands. In practice, however, this assumption is not always valid. The model accuracy may degrade when the assumption is violated. For example:

- Band #1: 900 MHz GSM signal; Band #2: 1800 MHz WCDMA, DCS or LTE signal.
- Band #1: 1.8 GHz WCDMA, DCS or LTE signal; Band #2: 5.4 GHz WiFi signal.

Consequently, the baseband Volterra model in [1] is not an adequate model for dual-band dual-band DPD design.

3. A GENERAL BASEBAND VOLTERRA MODEL

In this section, we derive the baseband dual-band Volterra model without any assumption on the carrier frequencies. The physical constraints of the frequency selectivity can be defined as follows:

$$\begin{cases} (a-b)\cdot\omega_{c_1} + (a+b+2c-l)\cdot\omega_{c_2} = \omega_{c_1}, \\ a+b+c \leq l. \end{cases} \quad (4)$$

$$\begin{cases} (a-b)\cdot\omega_{c_1} + (a+b+2c-l)\cdot\omega_{c_2} = \omega_{c_2}, \\ a+b+c \leq l. \end{cases} \quad (5)$$

Intuitively, when the constraints (4) and (5) hold, the corresponding high order harmonics or intermodulation products fall into one of the frequency bands and show up in the baseband representation.

Let us introduce

$$\frac{\omega_{c_1}}{\omega_{c_2}} = \frac{P}{Q}, \quad (6)$$

where P and Q are integers and are co-primes.

Substituting (6) in (4), we have

$$\begin{cases} (a-b-1)\cdot P = [l-(a+b+2c)]\cdot Q, \\ a+b+c \leq l. \end{cases} \quad (7)$$

The constraint (7) can be further simplified as

$$\begin{cases} a = M_1 \cdot Q + b + 1, \\ l = M_1 \cdot (P+Q) + 2(b+c) + 1, \\ a+b+c \leq l, \end{cases} \quad (8)$$

where

$$\lceil \frac{-(l+1)}{P+Q} \rceil \leq M_1 \leq \lfloor \frac{l-1}{P+Q} \rfloor. \quad (9)$$

The constraint (8) determines the intermodulation terms that show up in the first band.

Similarly, substituting (6) into (5), we have

$$\begin{cases} (a-b)\cdot P = [l+1-(a+b+2c)]\cdot Q, \\ a+b+c \leq l. \end{cases} \quad (10)$$

The constraint (10) can be further simplified as

$$\begin{cases} a = M_2 \cdot Q + b, \\ l = M_2 \cdot (P+Q) + 2(b+c) - 1, \\ a+b+c \leq l, \end{cases} \quad (11)$$

$$\tilde{y}(t) = \sum_{l=1}^{\infty} \int_{-\infty}^{+\infty} \cdots \int_{-\infty}^{+\infty} \tilde{h}_l(\tau_1, \cdots, \tau_l) \cdot (\frac{1}{2})^l \cdot \sum_{a=0}^{l} \Big\{ \mathrm{C}_l^a \cdot \prod_{i_1=1}^{a} z_1(t-\tau_{i_1}) \cdot e^{j\omega_{c_1}(a\cdot t - \sum_{i_1=1}^{a} \tau_{i_1})}$$
$$\cdot \{ \sum_{b=0}^{l-a} [\mathrm{C}_{l-a}^b \cdot \prod_{i_2=a+1}^{a+b} z_1^*(t-\tau_{i_2}) \cdot e^{-j\omega_{c_1}(b\cdot t - \sum_{i_2=a+1}^{a+b} \tau_{i_2})} \cdot (\sum_{c=0}^{l-a-b} \mathrm{C}_{l-a-b}^c \cdot \prod_{i_3=a+b+1}^{a+b+c} z_2(t-\tau_{i_3}) \cdot \prod_{i_4=a+b+c+1}^{l} z_2^*(t-\tau_{i_4})$$
$$\cdot e^{j\omega_{c_2}[(a+b+2c-l)\cdot t - \sum_{i_3=a+b+1}^{a+b+c} \tau_{i_3} + \sum_{i_4=a+b+c+1}^{l} \tau_{i_4}]})] \} \Big\} d\tau_1 d\tau_2 \cdots d\tau_l. \quad (3)$$

where

$$\lceil \frac{-l+1}{P+Q} \rceil \leq M_2 \leq \lfloor \frac{l+1}{P+Q} \rfloor. \quad (12)$$

From (9) and (12), we observe that the nonlinear intermodulation terms indeed fold into the operating band with selected M_1 and M_2. If $P+Q > l+1$, we have $M_1 = M_2 = 0$. This constraint suggest that the folded nonlinear intermodulation terms can be ignored since the nonlinear order is too high. In this case, the dual-band Volterra model reduces to the form shown in [1].

In the cases with $P+Q \leq l+1$, M_1 and M_2 can take nonzero values, whose items correspond to the harmonics or intermodulation products located in one of the operating bands. The proposed dual-band Volterra model can accurately represent the baseband nonlinearities while the dual-band Volterra model proposed in [1] may suffer in the modeling accuracy as well as the linearization performance degradation.

4. SIMULATION

In this section, we focus on the linearization performance of the dual-band DPD system with dual-band Volterra model proposed in [1] and the dual-band Volterra model proposed in this paper. The passband nonlinearity of the dual-band PA is described by a Saleh's model, which is given by:

$$\tilde{y}(t) = \frac{\alpha_a |\tilde{z}(t)|}{1+\beta_a |\tilde{z}(t)|^2} e^{j(\angle \tilde{z}(t) + \frac{\alpha_\phi |\tilde{z}(t)|}{1+\beta_\phi |\tilde{z}(t)|^2})}. \quad (13)$$

Table 1 shows the values of the coefficients for the Saleh's model used in this simulation. The dual-band Volterra model proposed in [1] and the dual-band Volterra model proposed in this paper are utilized to model the inverse nonlinear characteristics of the PA. The highest nonlinear order is 5 and the maximum memory depth is 2. The baseband input for band $\#1$ is a GSM signal with 200 kHz bandwidth, the corresponding carrier frequency is 935 MHz; the baseband input for band $\#2$ is a 4-carrier WCDMA signal with 20 MHz bandwidth, the corresponding carrier frequency is 1870 MHz. The least squares (LS) algorithm with 2000 data samples is utilized to estimate the model coefficients. Adjacent channel power ratio (ACPR) is applied in this simulation to compare the linearization performance of the dual-band Volterra model proposed in [1] and the dual-band Volterra model proposed in this paper.

Table 1: Values of the coefficients for the Saleh PA model.

Coefficients	α_a	β_a	α_ϕ	β_ϕ
Values	2	2.2	2	1

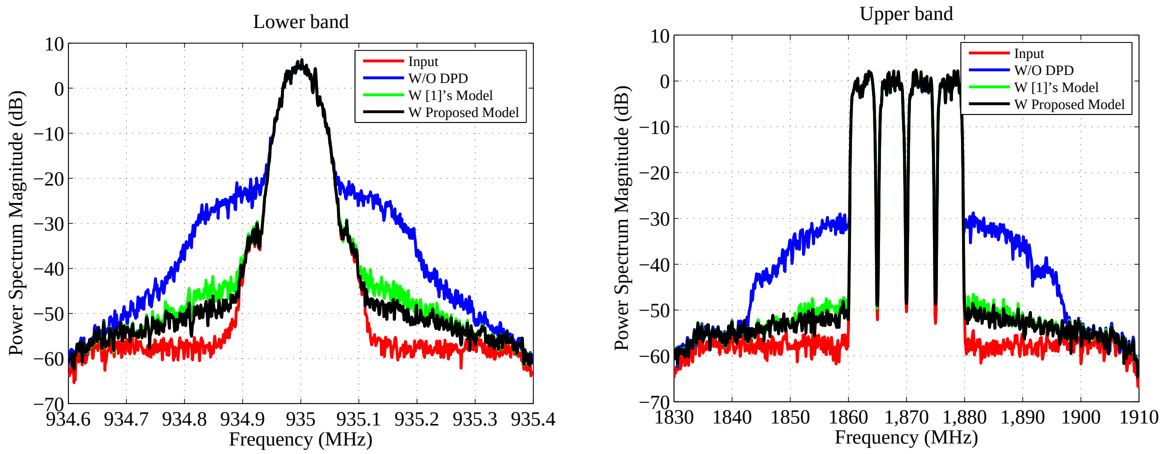
According to (6), we have $P=1, Q=2$. By setting the highest nonlinear order $L=5$, the ranges of M_1 and M_2 can be written as bellow:

$$\begin{cases} -2 \leq M_1 \leq 1, \\ -1 \leq M_2 \leq 2. \end{cases} \quad (14)$$

The corresponding values of a, b, c are shown in Table 2. In Table 2, the black items are included in the dual-band Volterra model proposed in [1] whereas the red items are not included in that model. On the contrary, all these items are included in the proposed dual-band Volterra model. For the dual-band Volterra model proposed in [1], the missing items can reduce the model accuracy and thus degrade the linearization performance.

In order to compare the overall linearization performance of the dual-band Volterra model proposed in [1] and the dual-band Volterra model proposed in this paper, power spectral densities (PSDs) at the PA input and output are simulated and shown in Fig. 2. In Fig. 2, the left one shows the PSDs of the lower band whereas the right one shows the PSDs of the upper band. From top to bottom, the blue line shows the PSDs at the PA output without DPD, the green line shows the PSDs at the PA output with the dual-band Volterra model proposed in [1], the black line shows the PSDs at the PA output with the dual-band Volterra model proposed in this paper, and the red line shows the PSDs at the PA input. In addition, the PSDs at the PA input are normalized to those at the PA output for easy visual comparison.

We observe from Fig. 2 that the linearization performance of the dual-band Volterra model proposed in this paper is better than that of the dual-band Volterra model proposed in [1]. As indicated in Fig. 2, the performance enhancements for lower band and upper band are about 3 dB and 2 dB, respectively.



(a) (b)

Fig. 2: Simulation results of the DPD performance with different dual-band Volterra models. The left one shows the PSDs of the lower band whereas the right one shows the PSDs of the upper band. From top to bottom, the blue line shows the PSDs at the PA output without DPD, the green line shows the PSDs at the PA output with the dual-band Volterra model proposed in [1], the black line shows the PSDs at the PA output with the dual-band Volterra model proposed in this paper, and the red line shows the PSDs at the PA input (normalized to the output power).

Table 2: The values of a, b, c with $\omega_{c_2} = 2\omega_{c_1}$ and $L = 5$.

Order	Band #1			Band #2		
	a	b	c	a	b	c
$l = 1$	1	0	0	0	0	1
$l = 2$	0	1	1	2	0	0
$l = 3$	1	0	1	0	0	2
	2	1	0	1	1	1
$l = 4$	0	1	2	0	2	2
	1	2	1	2	0	1
	3	0	0	3	1	0
$l = 5$	1	0	2	0	0	3
	2	1	1	1	1	2
	3	2	0	2	2	1
	0	3	2	4	0	0

5. CONCLUSION

In [1], the authors derived a dual-band Volterra model by linking the passband nonlinearity with the baseband representation. However, the derivations in [1] and other existing literature are based on the assumption that the out-of-band intermodulation products are far from the dual operating bands. Consequently, the model accuracy can be greatly degraded for some cases that disagree with that assumption. In this paper, we have redefined the physical constraints with no assumption on the nonlinear terms and derived a general baseband Volterra model for dual-band predistorter design. Specifically, the dual-band Volterra model that we proposed in [1] is a special case of the proposed model in this paper. Simulation results show that the dual-band Volterra model proposed in this paper outperforms the dual-band Volterra model proposed in [1]. The simulation shows that the proposed model has 2 dB improvement for both lower and upper bands in terms of ACPR performance.

6. REFERENCES

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