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2-D Polynomial-Based Model for the Dual-Band Concurrent Transmission in the Presence of Harmonic Interferences

Auwal Mustapha Imam

Department of Physics with Electronics, Federal University Birnin Kebbi, Nigeria

ABSTRACT: Generation of signals and corresponding trends for multiband, broadband, and ultra-wideband transmitters employ several models, some of which causes predistortion in a dual-band concurrent transmission. Two frequencies of operation are uncorrelated and harmonic products can be filtered out. However, when the harmonic of one signal falls on the frequency band of another signal, it cannot be removed with filters. This paper presents a 2-D harmonic polynomial based model for thedual-band concurrent transmission in the presence of harmonic interferences. Predistortion is implemented using a transmitter and a feedback receiver. With this model, a performance improvement of up to 22 dB in terms of normalized mean square error and performance improvement of up to 20 dB in terms of the adjacent channel power ratio is achieved compared to a dual-band polynomial model without harmonics.

KEYWORDS: Concurrent,Dual band, Frequency, Harmonic, Interference, Modeling, Power amplifiers, Predistortion, Polynomial, Signal.

I. INTRODUCTION

The multiband and multi-standard radio architectures allow for seamless transition from the older standard [e.g., third generation (3G)] to new standards [e.g., fourth generation (4G)] with backward compatibility [1], [2]. The upcoming generation of wireless communication signals [e.g., fifth generation (5G)], which are promoting schemes such as carrier aggregation techniques [3], requiring concurrent transmission of signals at more than one frequency band, has renewed interest in the design of dual-band [4], [5] and broadband [6] power amplifiers.

The concurrent operation of such dual-band power amplifiers with envelope exhibiting high signals gives rise to new in-band and out-of-band nonlinear distortions when the different nonlinear cross-products of the two signals interact with the bands of interest [7].

Research efforts have been focused towards improving stability, performance, and reducing application and algorithm complexity of the 2-D-DPD algorithm [8]. A cubic-spline-based model is proposed to replace polynomials in 2-D Digital Predistortion (2-D DPD) due to its better extrapolation properties [9]. A rational-functionbased two-step approach for better modeling performance is proposed in [10].

Some other research attempts have focused on the joint mitigation of modulator imbalance along with distortion arising from nonlinear concurrent dual-band operation. Arawat, *etal* in their paper tittled "Concurrent Dual-Band Modeling and DigitalPredistortion in the Presence of Unfilterable Harmonic Signal Interference" established that most of these models are variations of the same 2-D-DPD model, which is based on the frequency-selective assumption that the two bands of interest, their intermodulation, and harmonics by-products lie on separate frequencies. This assumption had been valid based on the practical bandwidth of most of the designed high-power power amplifiers, which provides bands up to 100–500 MHz apart while communication frequencies are in the gigahertz range.

However, the interference of harmonics has not been studied in dual-band concurrent transmitters. Therefore, this paper proposes a 2D-HMP model for modeling when one of the harmonics of the signal interferes with the upper band and cannot be removed using RF filters.

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II. NON-LINEAR TRANSMISSION

Non-linear transmission occursin a dual-band concurrent operation in a commonlyassumed scenario where the two bands lie on uncorrelated frequencies. Due to the interaction of signals at two bands, intermodulation and cross-modulation products are generated. The terms that fall outside the band-of-interest can be easily eliminated using a filter. Similarly, due to the imposed assumption of separate frequencies, the harmonics generated due to the signals also seem to fall outside the band of interest, and therefore, are needed to remove the distortions due to only the power amplifier nonlinearities, which affect the in-band signals via distortionand cross-modulation [11]. Figure 1studied scenario, where two frequencies of dual-band operation are uncorrelated.

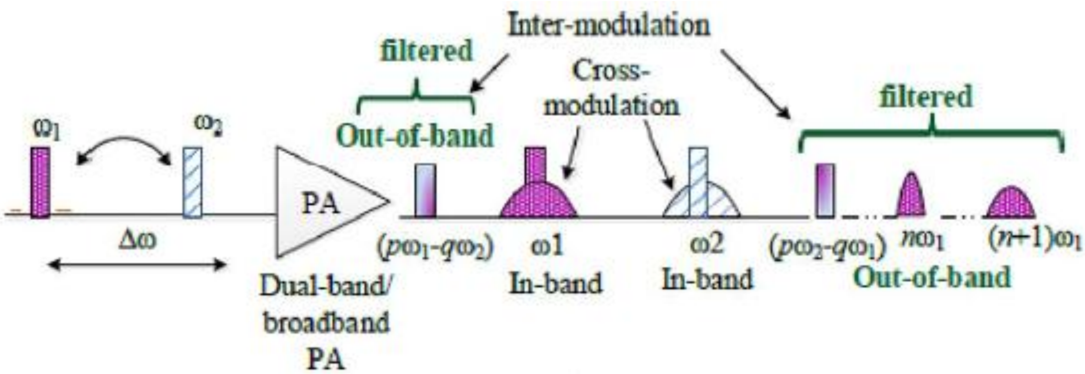

Fig. 1: The output of a nonlinear transmission

Recently, research in power amplifier design is pushing towards ultra-wideband application [12], which, in turn, raised concern of interference from harmonics, which might fall within the working range of ultra-wideband power. Keeping this trend in mind, there had been very few recent attempts to model power amplifier harmonics. Harmonic cancellation feed forward techniques are proposed in [13] by injecting an uncorrelated signal at harmonic frequency, whereas [14] proposed a tunable third harmonic elimination technique for envelope-tracking amplifiers.

III. DUAL-BAND MODEL WITH HARMONIC FREQUENCIES

Two-band fundamental envelope power amplifier model before developing a two-band model for a power amplifier, it is useful tofirst consider the case where a two-tone input excitationand at frequency and , respectively, is applied atthe input port of the power amplifier.

It can be verified that the resulting odd-order intermodulation terms of the output below can be described with a Volterra system [15] as

$$b_{out}\left(\frac{p+1}{2}\omega 1 - \frac{p-1}{2}\omega 2\right) = V^{-}_{p} \cdot a_{in}^{(p-1)/2}\,\omega 1 \cdot a_{in}^{*(p-1)/2}\,\omega 2 \qquad 1$$

With p being an odd integer

Explicit equations for the above terms up to seventh order are given by

$$b_{out}(4\omega 1 - 3\,\omega 2) = V_7^{-} \cdot a^4_{in}(\omega 1) \cdot a^3_{in}(\omega 2) \qquad 2$$

$$b_{out}(3\omega 1 - 2\omega 2) = V_5^{-} \cdot a^3_{in}(\omega 1) \cdot a^2_{in}(\omega 2) \qquad 3$$

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$b_{out}(2\omega 1 - \omega 2) = V_3^- \cdot a^2_{in}(\omega 1) \cdot a_{in}(\omega 2)$ 4

$b_{out}(\omega 1) = V_1^- \cdot a_{in}(\omega 1)$ 5

Similarly, the resulting odd order intermodulation terms b_{out} above ω2 at the power amplifier output can also be described with a Volterra system as ;

$$b_{out}\left(\frac{p+1}{2}\omega 2 - \frac{p-1}{2}\omega 1\right) = V^+_p \cdot a_{in}^{(p+1)/2}\omega 2 \cdot a_{in}^{*(p-1)/2}\omega 1 \quad 6$$

With the explicit expansion of the terms up to seventh order given by;

$b_{out}(\omega 2) = V_1^+ \cdot a_{in}(\omega 2)$ 7

$b_{out}(2\omega 2 - \omega 1) = V_3^+ \cdot a^2_{in}(\omega 2) \cdot a_{in}(\omega 1)$ 8

$b_{out}(3\omega 2 - 2\omega 1) = V_5^+ \cdot a^3_{in}(\omega 2) \cdot a^2_{in}(\omega 1)$ 9

$b_{out}(4\omega 2 - 3\omega 1) = V_7^+ \cdot a^4_{in}(\omega 2) \cdot a^3_{in}(\omega 1)$ 10

Where the Volterra function

$V_k^{\pm} = V_k^{\pm}(|a_{in}(\omega_1)|^2, |a_{in}(\omega_2)|^2)$ are functions of two envelopes.

Consider the case of two modulated input signals x_1 and x_2 at the frequencies $\omega_1 = \omega + \Delta$ and $\omega_2 = 2\omega$ with. To identify the output intermodulation terms resulting near the two bands in concurrent operation, it is convenient to first consider the case of a narrowband two-tone signal at these center frequencies.
After performing a Volterra-series expansion for the near-band signal components, it is observed that both even and odd intermodulation components fall near the first and second bands. These terms can also be practically observed in Figures 2 and 3, which show the intermodulation by-products generated near the bands of interest at the output of an ultra-wideband when excited by a two-tone signal.

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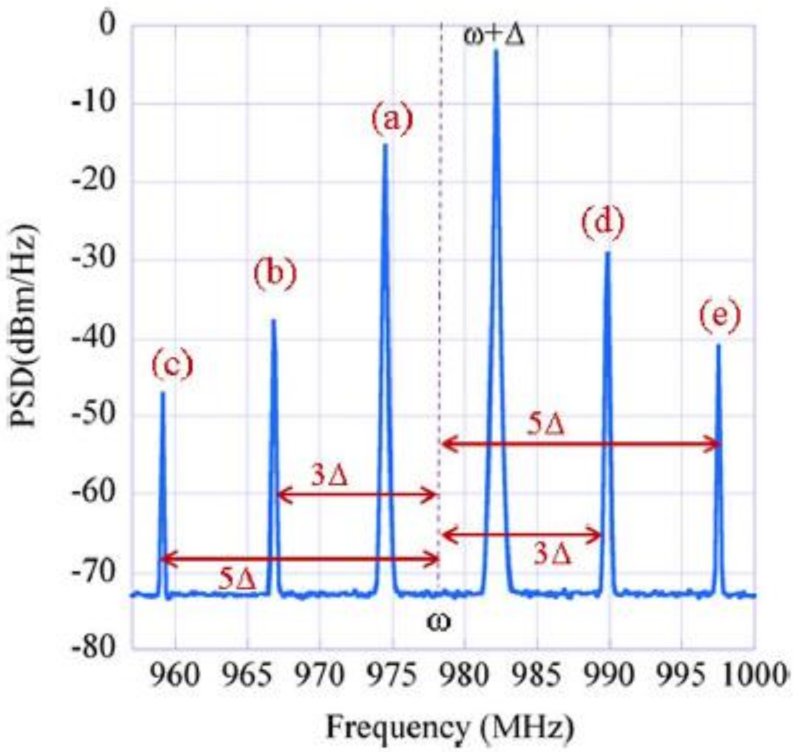

Figure 2: Intermodulation terms interfering with the lower band (ω+ Δ) [5]

The lower-band lower frequency side components in fig. 2 are given by

$b_{out}(\omega 1 - 2q\Delta) = V^{q}_{1,2} \,.\, x^{a}_{2}(\omega) \,.\, x_1^{*(}2q - 1)$ 11

The lower band upper frequency side components in Fig. 2 are given as

$b_{out}(\omega 1 + 2q\Delta) = V^{q}_{1,3} \,.\, x^{a}_{2}(\omega) \,.\, x_1^{*(}2q + 1).\, x_2{*}^{q}$ 12

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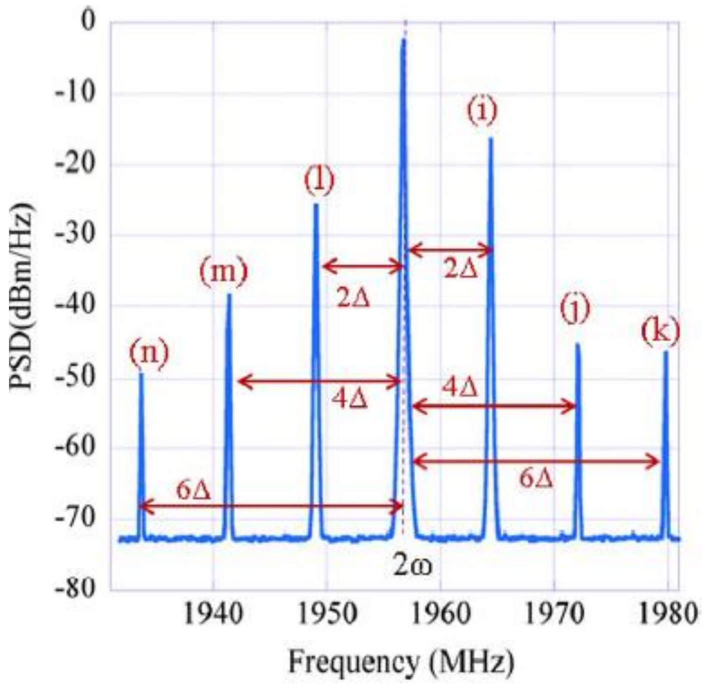

Figure 3: Intermodulation terms interfering with the upper band (2ω) [5]

The upper band lower frequency side component in Fig. 3 are given as

$$b_{out}(\omega 2 - 2q\Delta) = V^{q}_{2,2} \cdot x_2^{(q+1)} \cdot x_1^{2q}{}_1 \qquad 13$$

The upper band upper frequency side components in Fig. 3 are given as

$$b_{out}(\omega 2 + 2q\Delta) = V^{q}_{2,3} \cdot x^{2q}{}_1 \cdot x_1^{*2q} \cdot x_2{*}^{(q-1)} \qquad 14$$

The frequency ranges of concurrent communication components mostly cover only the fundamental and second harmonic. However, using similar analysis, the interfering intermodulation distortion (IMD) terms for signals at ω and pω center frequency bands can be calculated. For the case of a second harmonic interference with the Volterra model for the system can be compactly represented using

$$b_{out}(\omega) = V_{1,1} \cdot a_{in}(\omega) + V_{1,2}\, a^{*}{}_{in}(\omega) \cdot a_{in}(2\omega) \qquad 15$$

$$b_{out}(2\omega) = V_{2,1} \cdot a_{in}(2\omega) + V_{2,2}\, a^{2}{}_{in}(\omega) \qquad 16$$

IV. 2-D HARMONIC MEMORY POLYNOMIAL (2D-HMP) MODEL

Considering the two input and output baseband signals (x_1, x_2) and (y_1, y_2) respectively at the two carrier frequencies, the generalized complex-baseband input/output relationship of the 2D-MP model for concurrent dual band, with the K^{th}nonlinearity order is expressed as: [16]

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$$y_b(n) = \sum_{m=0}^{M-1} x_b(n-m) \cdot \sum_{k=0}^{K-1} \sum_{j=0}^{k} c_{m,k,j}^{(b)} \cdot |x_b(n-m)|^{k-j} \cdot |x_p(n-m)|^{j}$$

17

Where $b, p \in \{1, 2\}$, $b \neq p$; b and p represents the first band p of interest and the second band p, respectively. $c_{m,k,j}^{(b)}$ are the coefficients of the model and represents the memory depth. This model captures the in-band cross-modulation between the two-band signals. There are two carrier frequencies ω and 2ω due to the presence of the new intermodulation distortions terms. Accounting for these terms, a new 2D-HMP model is given as follows for the lower and upper band signals:

$$y_1(n) = \sum_{m=0}^{M_l} V_{1,1}^{m,0}(n-m) \cdot x_1(n-m) + \sum_{m=0}^{M_l} \sum_{q=1}^{Q_l} V_{1,2}^{m,q}(n-m) \cdot {x_2}^{q}(n-m) \cdot {x_1}^{*(2q-1)}(n-m) + \sum_{m=0}^{M_u} \sum_{q=1}^{Q_u} V_{1,3}^{m,q}(n-m) \cdot {x_1}^{2q+1}(n-m) \cdot {x_2}^{*q}(n-m)$$

$$y_2(n) = \sum_{m=0}^{M} V_{2,1}^{m,0}(n-m) \cdot x_2(n-m) + \sum_{m=0}^{M_l} \sum_{q=1}^{Q_l} V_{2,2}^{m,q}(n-m) \cdot {x_2}^{q+1}(n-m) \cdot {x_1}^{*2q}(n-m) + \sum \sum_{M_u}^{Q_u} V_{2,3}^{m,q}(n-m)$$

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$$\cdot {x_1}^{2q}(n-m) \cdot {x_2}^{*(q-1)}(n-m)$$

Where $V_{b,p}^{m,q}(n)$ are functions of the form $V_{b,p}^{m,q}(n) = V_{b,p}^{m,q}\left(|x_1(n)|\,,|x_2(n)|\right)$
When using a polynomial expansion, we have;

$$V_{b,p}^{m,q}\left(|x_1(n)|\,,|x_1(n)|\right) = \sum_{k=0}^{K_l}\sum_{j=0}^{k} a_{k,j}^{b,p,m,q} \cdot |x_2(n-m)|^{k-j} \cdot |x_1(n-m)|^{j}\,. \quad 18$$

V. CONCLUSION

It can be observed that for a captured input–output measurement data set, the model is linear with respect to its coefficients and represent the intermodulation product orders. Similar to 2-D DPD, the coefficients for the lower and upper bands can be calculated using the least square (LS) method. This paper has discussed the effect of concurrent dual-band transmission when the harmonic of the lower band signal directly interferes with the signal in the upper band such that it cannot be removed with an RF filter. The paper is also focused on the case where the upper band signal is at the second harmonic of the lower band signal. This paper has proposed a 2D-MP model based on inter-mode analysis of a nonlinear power amplifier for the dual-band concurrent transmission in the presence of harmonic interferences.

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