Suboptimal Multimetric Model Extraction for Digital Predistortion of RF Power Amplifiers

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***Abstract*—Different linearity requirements in different frequency regions, namely, the multimetric linearity requirements, may arise when coordinating the spectrum resources in wireless systems. Conventional digital predistortion (DPD) model extraction techniques are expected to be inefficient in this scenario as only the metric of normalized mean square error (NMSE) is considered. This work addresses the challenge by establishing a mathematical framework to distinguish the linearity error in different frequency regions, and then proposing an enhanced quadratic simultaneous perturbation stochastic approximation (Q-SPSA) targeting the DPD model extraction for multimetric requirements. Substantial experimental results confirm that the proposed method can find suboptimal solutions of DPD model coefficients that just meet the multimetric requirements with much fewer computational resources, hence bringing about the potential of saving digital processing power for upcoming systems with multimetric linearity requirements.**

***Index Terms*—Digital predistortion (DPD), multi-objective optimization, power amplifier (PA), simultaneous perturbation stochastic optimization (SPSA).**

I. Introduction

TO fully exploit the potential of wireless systems, transmitters will work in coordination to negotiate the spectrum resources [1]. As a result, different linearity requirements in different frequency regions, i.e., the multimetric requirements, will arise. As illustrated in Fig. 1, for some specific wireless transmitter, its nonlinearity may need to be suppressed to different levels in different frequency regions. The solid curve represents the original distortion level distribution in frequency domain without introducing DPD linearization, while the dashed line shows the required linearity error levels in different regions. In in-band regions, the strictness may vary in strictness depending on modulation order deployed, e.g., higher order modulation such as 4096-QAM requires superior linearity. Besides, in out-of-band regions, the strictness may also be different subject to channel occupations, e.g., the linearity error in heavily occupied regions must be suppressed to lower levels to avoid impacting other transmitters using the channel.

Conventional methods for extracting DPD coefficients such as [2] will be inefficient since they focus solely on minimizing the error metric of normalized mean square error (NMSE), which sums the error at all samples in the time domain but does not has the ability to distinguish the error in different frequency regions. Furthermore, the least square (LS) algorithm is usually used to extract coefficients with optimal performance but involves very high computational complexity. In fact, the suboptimal coefficients just satisfying the requirement are sufficient in practice. Thus, low-complexity iterative model extraction algorithms such as the quadratic simultaneous perturbation stochastic approximation (Q-SPSA) [3] is of growing interest. However, it is still based on NMSE only.

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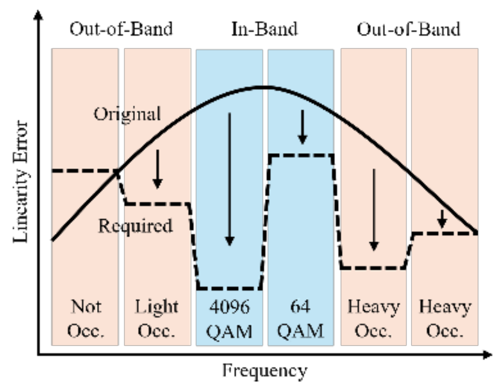

Fig. 1. Multimetric linearity requirements

To address the challenges, this work firstly establishes a mathematical framework to distinguish the linearity error in different frequency regions, then expands the Q-SPSA algorithm for multimetric applications and proposes a better way for calculating the Q-SPSA progression step. Relevant contents are published in [4] and [5], while this report will introduce some of the highlights.

II. Distinguishing the Linearity Error

The extraction of DPD coefficients in conventional methods such as [2] is based on minimizing the loss function of summed error in the time domain, i.e.,

$$L(\mathbf{e}) = \mathbf{e}^H \mathbf{e} \tag{1}$$

where $\mathbf{e}$ is the linearity error signal. To realize effective multimetric linearization, the error in specific frequency region(s) can be distinguished as

$$L(\mathbf{e}) = \mathbf{e}^H \mathbf{F}^H \mathbf{B} \mathbf{F} \mathbf{e} \tag{2}$$

where $\mathbf{F}$ is the normalized discrete Fourier transform (DFT) matrix, and $\mathbf{B}$ is a diagonal matrix that designates frequency region(s) of interest. Examples for using (2) to calculate the error in different regions are illustrated in Fig. 2.

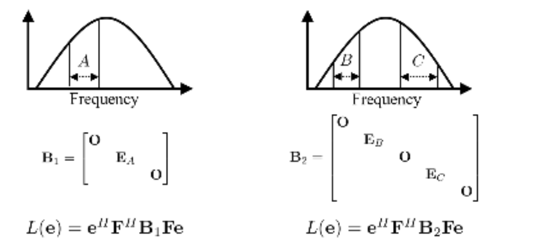

Fig. 2. Distinguishing the linearity error in different frequency regions.

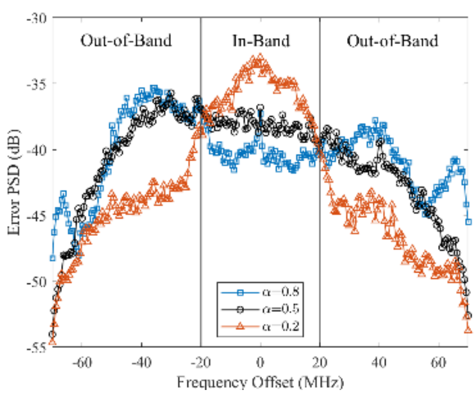

Fig. 3. Error PSD comparison at the same NMSE threshold.

III. Enhanced Q-SPSA for Multimetric Extraction

The conventional Q-SPSA [3] merely based on NMSE is expanded to multimetric applications, and then enhanced by adopting a better way for progression step calculation, which brings about lower complexity and better numerical stability. The proposed enhanced Q-SPSA step for multimetric model extraction is,

$$\mathbf{C}_{h+1} = \mathbf{C}_h - \frac{R\{\boldsymbol{\Delta}_h^H \mathbf{X}_h^H \mathbf{F}^H \boldsymbol{\Psi} \mathbf{F} \mathbf{e}_h\}}{\boldsymbol{\Delta}_h^H \mathbf{X}_h^H \mathbf{F}^H \boldsymbol{\Psi} \mathbf{F} \mathbf{X}_h \boldsymbol{\Delta}_h} \boldsymbol{\Delta}_h \tag{3}$$

where $\mathbf{C}$ denotes coefficients to be extracted, h is the iteration index, $R\{\cdot\}$ is the real part operator, $\boldsymbol{\Delta}$ is the perturbation vector, $\mathbf{X}$ is the matrix built from nonlinear kernel functions, and $\boldsymbol{\Psi} = \alpha^2\mathbf{B}_1 + (1-\alpha)^2\mathbf{B}_2$ is a matrix for adjusting the relative significance of error in different frequency regions, in which α is the weighting factor. Some of the most representative results achieved by (3) will be introduced. In Fig. 3, the power spectrum density (PSD) curves for error achieved using different α settings are compared, in which the $\alpha = 0.5$ is equivalent to the method in [3] that only considers NMSE. By setting different factors of $\alpha = 0.8$ and $\alpha = 0.2$, the proposed method can achieve different error PSD distributions at the same NMSE threshold, in which $\alpha = 0.8$ corresponds to lower IB error while $\alpha = 0.2$ corresponds to lower OOB error. The numerical results on error vector magnitude (EVM) and adjacent channel power ratio (ACPR) given in Table I and Table II then further confirm that the proposed method can realize preferred optimization of the linearity error in different frequency regions, which saves significant computational resources in terms of floating point operations (FLOPS).

TABLE I
EVM Priority Optimization

EVM without DPD (%) = 6.16				
EVM Requirement (%)	α	Iterations	Normalized Complexity	Reduction of FLOPS (%)
4.00	0.8 0.5*	32 89	38.08 89	57.21
3.00	0.8 0.5*	322 537	383.18 537	28.64
2.00	0.8 0.5*	1119 1677	1331.61 1677	20.60
1.50	0.8 0.5*	2395 3326	2850.05 3326	14.31

*Equivalent to the method in [3] that only considers NMSE.

TABLE II
ACPR Priority Optimization

ACPR without DPD (dBc) = –32.26/-34.88				
ACPR Requirement (dBc)	α	Iterations	Normalized Complexity	Reduction of FLOPS (%)
-35.00	0.2 0.5*	328 1074	390.32 1074	63.66
-37.00	0.2 0.5*	1023 2221	1217.37 2221	45.19
-39.00	0.2 0.5*	1513 4382	1800.47 4382	58.91

*Equivalent to the method in [3] that only considers NMSE.

IV. Career Plan and Fellowship Impact

I would like to thank the IEEE MTT-S for recognizing my contributions and awarding me the honorable graduate fellowship. The fellowship provides not only financial support but also invaluable encouragements as I explore the uncharted territories in my research. As the end of my PhD journey approaches, I would also like to express my sincere gratitude to my supervisor Prof. Anding Zhu. After graduation, my current plan is to work in the industry of RF algorithms and may return to academia later. The attendance of IMS2023 in San Diego was so impressive, as I met new friends with great passions in the field of microwave engineering.

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