Performance Optimization of GaN HEMTs by combined RF and LF wideband load-pull

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***Abstract*—The project aims at demonstrating how to maximize a given figure of merit (FoM) of a radio-frequency (RF) power amplifier (PA) by setting suitable wideband terminations at both RF and low-frequency (LF). These wideband terminations can be practically set through active load-pull, where the actual injected signals are found through global numerical optimization. The problem can be compactly treated as a generalized digital predistortion (DPD) method, where the DPD coefficients represent the optimization variables. Preliminary experimental results on a Gallium Nitride (GaN) PA, in which only the RF source injection is optimized, have shown that the proposed approach outperforms the classic DPD indirect learning architecture for a memory-polynomial-based predistorter of given nonlinearity and memory orders.**

***Index Terms*—power amplifiers, digital predistortion.**

I. Introduction

THE behavior of radio-frequency (RF) power transistors under large-signal operating conditions is determined by the impedance terminations seen by the device at the RF carrier frequency and its harmonics, including dc. Sweeping the impedance loads by means of load-pull (LP) techniques allows to find the optimal terminations for a given figure of merit (FoM), e.g., the average RF output power or power-added efficiency (PAE). When wide-bandwidth (BW) modulated signals are used, wideband active LP might involve sweeping terminations at many frequencies points. However, characterizing all combinations of impedance states is an unpractical and time-consuming task. In this context, transforming LP characterization sweeps into an optimization problem aimed at finding the best broadband terminations for a given FoM seems an attractive possibility. Nevertheless, also this process must account, in principle, for a large number of complex variables, i.e., one for each frequency points at each controlled termination.

In order to reduce the dimensionality of the problem, the optimal injected signals for a given transistor termination can be obtained through a digitally-implemented parametric processing block. Such a block realizes a generic nonlinear dynamic system capable to flexibly process the input signal to be amplified, yet using a reduced number of parameters to be optimized. As an example, the block can implement a Volterra-like system using a memory polynomial representation with a given nonlinearity order and memory depth. Actually, this framework resembles the digital predistortion (DPD) concept, yet applied not only for the RF source, but also at the other PA terminations. Thus, the complex DPD coefficients of the predistorter blocks become the tuning variables to be obtained by optimization.

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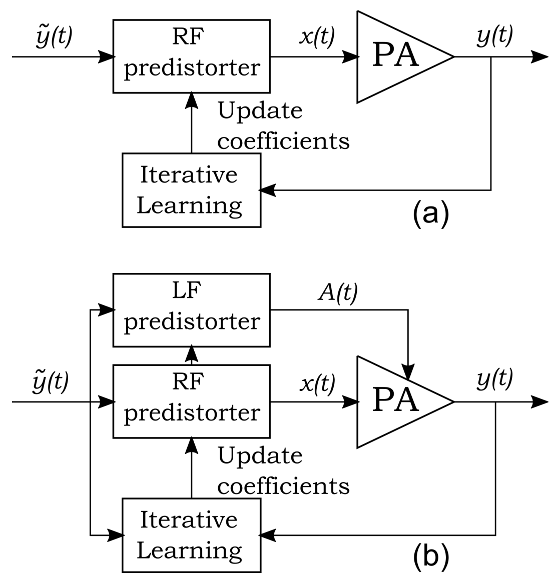

Fig. 1. (a) DLA and (b) DLA with supply control.

This process can be actually thought as corresponding to the Direct Learning Architecture (DLA) DPD implementation (Fig. 1a), where the coefficients are identified by means of some nonlinear optimization strategy (typically iterative). The DLA can thus be extended to other device terminations as shown in Fig. 1b, where an LF predistorter block is added to control the drain supply termination.

II. Optimization method

Using the notation in Fig. 1, a generic predistorter can be represented in a matrix form as $\mathbf{x} = \mathbf{H}\boldsymbol{\phi}$, where $\mathbf{H}$ is the regression matrix derived from the delayed samples of $\tilde{y}$, and ϕ is the DPD coefficients vector for a given predistorter parametric model. The baseband supply control signal $\mathbf{A}$ is likewise obtained by $\mathbf{A} = \mathbf{H}\boldsymbol{\phi}$, with $\mathbf{H}$ and ϕ using the same notation yet different values. The same formalism could be extended to the RF load termination. Therefore, the mathematical problem of optimizing a scalar FoM $f(\boldsymbol{\phi})$ when a constraint $g(\boldsymbol{\phi})$ is imposed can be formalized as:

$$\max_{\boldsymbol{\phi}} \; f(\boldsymbol{\phi}) \quad \text{subject to } g(\boldsymbol{\phi}) < \eta \tag{1}$$

where η is a scalar quantity and depends on the application. A gradient-based iterative algorithm is proposed to reach the optimum:

$$\boldsymbol{\phi}_{i+1} = \boldsymbol{\phi}_i + \lambda_f \mathbf{D}_f; \quad \mathbf{D}_f = \boldsymbol{\nabla} f(\boldsymbol{\phi}_i), \tag{2}$$

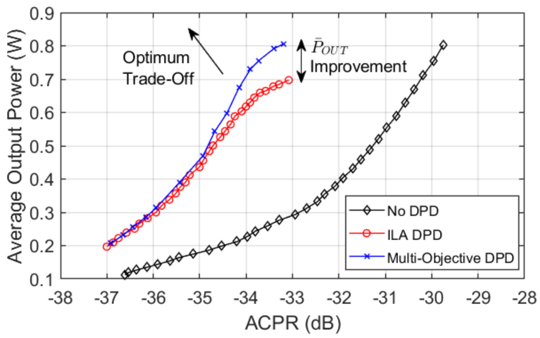

Fig. 2. DPD performance when $\bar{P}_{OUT}$ is maximized and the ACPR is a constraint.

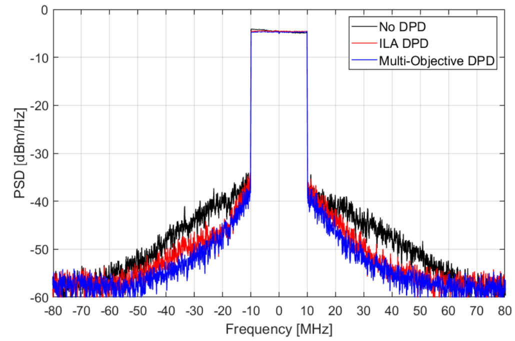

Fig. 3. Frequency spectra showing the performance of the proposed multi-objective optimization against a classic ILA approach for the same level of $\bar{P}_{OUT} \simeq 0.7$ W.

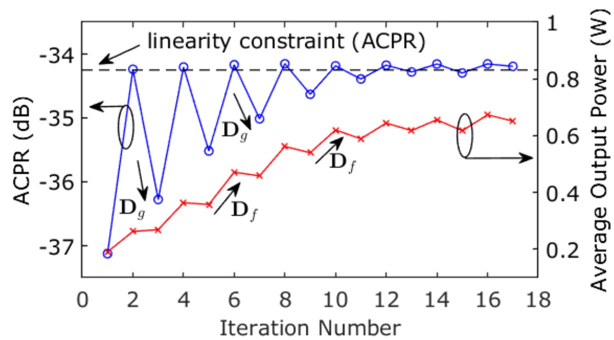

Fig. 4. Iterative behavior of the algorithm, where the conflicting optimization directions $\mathbf{D}_g$ (constraint) and $\mathbf{D}_f$ (maximization) are indicated.

where the gradient, corresponding to the optimization direction $\mathbf{D}_f$, is obtained through a finite differences approximation, while $\lambda_f \in [0,1]$ is the step size dynamically set at each iteration. If the constraint $g(\boldsymbol{\phi}_i) < \eta$ is not satisfied, an optimization direction $\mathbf{D}_g$ must be obtained to account for the constraint at the next iteration. The calculation of $\mathbf{D}_g$ is based on the ILC approach [1], which minimizes the following instantaneous complex error between the (scaled) desired and the measured output signals:

$$\mathbf{e}_i = \tilde{\mathbf{y}} \frac{\max\{\mathbf{y}_i(n)\}}{\max\{\tilde{\mathbf{y}}(n)\}} - \mathbf{y}_i. \tag{3}$$

Such minimization is achieved by an iterative procedure, where the optimized PA input at the ith iteration is obtained as $\mathbf{x}_{i+1} = \mathbf{x}_i + \boldsymbol{\Gamma}_i \mathbf{e}_i$, where $\boldsymbol{\Gamma}_i$ is a diagonal matrix containing the values of the instantaneous gain $G_i(n) = \frac{y_i(n)}{x_i(n)}$ for each sample. Direction $\mathbf{D}_g$ should be defined with respect to the coefficients $\boldsymbol{\phi}$, so we first express the $\boldsymbol{\phi}$ in terms of $\mathbf{x}$ and $\mathbf{H}$ by inverting the predistorter model and obtaining $\boldsymbol{\phi} = \mathbf{H}^{\dagger}\mathbf{x}$, where $\mathbf{H}^{\dagger} = (\mathbf{H}^{+}\mathbf{H})^{-1}\mathbf{H}^{+}$ is the pseudoinverse of $\mathbf{H}$. Then, the formula for the ith iteration and the relative direction results:

$$\boldsymbol{\phi}_{i+1} = \boldsymbol{\phi}_i + \lambda_g \mathbf{D}_g; \quad \mathbf{D}_g = \mathbf{H}^{\dagger}\boldsymbol{\Gamma}_i \mathbf{e}_i, \tag{4}$$

where $\lambda_g \in [0,1]$ is the step size dynamically set at each iteration. As the constraint is satisfied, the next iteration goes towards the maximization of f until reaching the constrained optimum.

III. Preliminary Results

The algorithm has been preliminary applied to maximize the average RF output power for a given Adjacent Channel Power Ratio (ACPR) constraint in a classic DPD setting. The device-under-test (DUT) is a Gallium Nitride (GaN) PA (Cree CGH40006-TB) at 2 GHz carrier frequency, characterized by means of the setup in [2]. The predistorter is described by a memory polynomial model with the fixed orders $K = 5$ and $M = 3$. The input test signal is a 20-MHz-BW, random-phase 2k-tone with peak-to-average power ratio (PAPR) of 9 dB. The measured results are reported in Fig. 2. The curve obtained with the proposed multi-objective algorithm lays closer to the $\bar{P}_{OUT}$ - linearity optimum, outperforming a classic Indirect Learning Architecture (ILA) for the same number of DPD coefficients. In Fig. 3, we compare the output frequency spectra obtained with the two DPD approaches. Finally, Fig. 4 reports the iterative behavior of the algorithm, highlighting the dynamic change in the optimization direction between the one kept to maintain the ACPR below the limit imposed ($\mathbf{D}_g$) and the $\bar{P}_{OUT}$ maximization ($\mathbf{D}_f$). While these results have been submitted for publication, future work will involve controlling the drain supply impedance and the load terminations, as well as considering different FoMs e.g., PAE.

IV. Impact Statement and Career Plans

The MTT-S scholarship allowed me to fully concentrate on an extended thesis work, during which I have developed scientific interests in the microwave field. After the M. Sc. graduation, I wish to undertake a Ph.D. program at the University of Bologna and continue the research on PA performance optimization.

References

[1] J. Chani-Cahuana, P. N. Landin, C. Fager, and T. Eriksson, "Iterative Learning Control for RF Power Amplifier Linearization," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 9, pp. 2778–2789, 2016.

[2] P. N. Landin, S. Gustafsson, C. Fager, and T. Eriksson, "WebLab: A web-based setup for PA digital predistortion and characterization [Application Notes]," *IEEE Microwave Magazine*, vol. 16, no. 1, pp. 138–140, 2015.