Multiple-Input RF PAs Digital Predistortion by Machine Learning Optimization

Mattia Mengozzi, *Student Member, IEEE,* Gian Piero Gibiino, *Member, IEEE,*
and Alberto Santarelli *Member, IEEE*

***Abstract*—This document describes the research that was conducted over the past few months with the support of the MTT-S Graduate Fellowship. The focus of the research was on developing novel digital predistortion (DPD) techniques for multiple-input RF power amplifiers exploiting multi-objective optimization (MOO) and machine learning (ML). Two significant applications of this concepts were presented in this work. Firstly, DPD-based MOO framework is described and applied to a dual-input Doherty PA (excited with up to 100MHz bandwidth signals at Ka-band). Secondly, a solution for realizing beam-dependent linearization of microwave active beamforming PA arrays exploiting a ML approach is presented.**

***Index Terms*—digital input control, dual-input power amplifiers, beamforming array, linearization, machine learning**

I. INTRODUCTION

During the last decades, multiple-input (MI) power amplifiers (PAs), such as dual-input Doherty PAs (DDPAs) and MI PAs arrays, have been the subject of extensive research to improve their inherent linearity-efficiency trade-off for high peak-to-average power ratio signals. Modern PA topologies realize load modulation by means of multiple transistor-based amplifier. These have been demonstrated in both microwave monolithic integrated circuit (MMIC) and discrete realizations, yet mostly for the sub-6 GHz applications and for reduced instantaneous BWs. Realizing similar advances in the Ka band for GHz-wide BWs and performing the due performance assessment requires renewed research efforts. The conventional approach of using single-input single-output DPD is limited by the inherent differences between the PAs and the changing dynamic loading condition in MI PA architectures.

The following sections present two works that implement this concepts to a DDPA and a beamforming PA array. The first work led to a publication [1], while the second [2] will be presented at the International Microwave Symposium 2023 as technical paper.

II. DUAL-INPUT DOHERTY PA OPTIMIZATION

In [1], a method to optimize the input split and bias voltage of a DDPA using MOO is presented. The proposed method improves the power-added efficiency (PAE) of the PA by optimizing the input split and bias voltage simultaneously. The algorithm exploits a bayesian optimization and a surrogate model to identify a better trade-off among PAE and the average RF output power of the device-under-test (DUT). Simulation results show that the proposed method achieves a PAE improvement of up to 7.9% compared to nominal Doherty PAs. This work provides a practical and effective method for optimizing the performance and better explore trade-offs of a digitally controlled DDPA.

In order to validate this approach through measurements, a customized control of the input excitations applied to the dual-input DUT must be realized on a wideband 3-port on-wafer maeasurment setup. This preliminary work aims at realizing this control in order to digitally synthesize the electrical conditions of a passive splitter at the input of the DDPA. The emulated splitting ratio and phase, denoted by α and ϕ, respectively, are the two parameters that are being controlled across the whole bandwidth of interest. To achieve the desired splitting conditions and linearize the emulated DDPA, a nested iterative-learning-control [3] scheme is proposed. An outer loop realizes the DPD, while an inner loop sets the correct splitting conditions between the two inputs by updating the auxiliary branch of the DDPA. After convergence is reached for the inner loop, the two analog inputs a_1 and a_3 of the DDPA should satisfy the conditions imposed by the theoretical quadrature hybrid for the given α and ϕ values.

The DUT is a Microwave Monolithic Integrated Circuit technology DDPA, that is designed in the NP15-00 150-nm GaN-on-SiC process by WIN Semiconductors. It features a two-stage amplification technique, which enables it to achieve a gain of 25 dB at a frequency of 24 GHz.

Fig. 1 represents a preliminary characterization of the DDPA under a wideband modulated signal. The blue line in Fig. 1a corresponds to the output b_2 wave for the DDPA after imposing the emulation of the splitting hybrid (after DPD linearization), resulting in adjacent channel power ratio (ACPR) of -48.8 dB and error vector magnitude (EVM) of -43.7 dB, whereas the red curve corresponds to the injected wave a_1 to the main branch of the DDPA. In this distorted condition, the average output power is $P_{out}^{RMS} = 20.1$ dBm and a peak power $P_{out}^{Max} = 29.3$ dBm. Figure 1b shows the iterative behavior of the inner loop to set the desired α and ϕ.

III. ACTIVE ARRAY LINEARIZATION

The proposed architecture in Fig. 2 aims to develop an open-loop beam adapter (BA) for DPD, which adjusts the DPD coefficients and operating conditions in a predictive manner without requiring feedback from the array output. The open-loop beam-dependent DPD (BD-DPD) model is represented

---

The authors are with the Dept. Electrical, Electronic, and Information Engineering "G. Marconi," University of Bologna, 40136 Bologna, Italy (e-mail: mattia.mengozzi3@unibo.it).

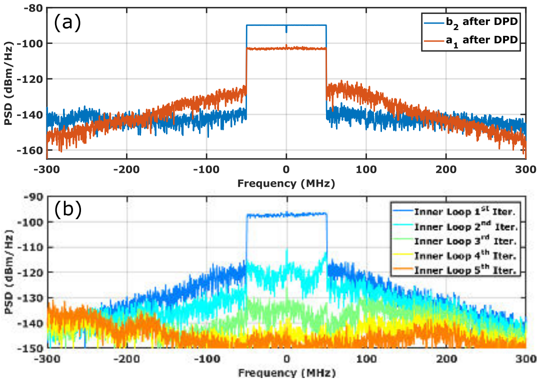

Fig. 1. DDPA waves after linearization: (a) $\mathbf{b}_2$ and $\mathbf{a}_1$ spectra, (b) a_3 spectrum through the ILC-based inner loop for dual input control.

as $\boldsymbol{y} = \boldsymbol{X}\boldsymbol{c}(\theta, \rho)$, where $\boldsymbol{y}$ is the predistorter output, $\boldsymbol{X}$ is the model regression matrix based on the input $\boldsymbol{x}$, and $\boldsymbol{c}$ are the varying predistorter coefficients that depend on the beam angle (θ) and input signal peak-to-average power ratio (PAPR) (ρ). The approach is divided into two phases: offline pre-training and real-time linearization. In the pre-training phase, the open-loop BD-DPD generator model parameters are identified, and the data obtained from linearizing the PA array for a subset Γ of operating conditions are used to extract the BA model $\boldsymbol{c}(\theta, \rho)$. In the online linearization phase, the DPD coefficients are adjusted by the BA in a predictive manner based on the given beam angle and input signal PAPR, without requiring real-time feedback.

The ML-based feature reduction method [4] employed by the BA utilizes a transformation matrix $\boldsymbol{A}$ to approximate the behavior of a PA across various operating conditions using a reduced set of features. This can be expressed as $\boldsymbol{y} = \boldsymbol{X}\boldsymbol{c}(\theta, \rho) \simeq \boldsymbol{X}\boldsymbol{A}\boldsymbol{\omega}(\theta, \rho)$, where $\boldsymbol{\omega}(\theta, \rho)$ is a vector of coefficients acting as a BA and has lower dimensionality compared to $\boldsymbol{c}(\theta, \rho)$. Ultimately, it is possible to derive a global BA model $\boldsymbol{\omega}(\theta, \rho)$ by interpolating the $\boldsymbol{\omega}$ values over various beam angles (θ) and input power levels (ρ). This study utilized either a 2D cubic spline model or a cubic polynomial model to carry out the interpolation.

The measurement validation of the method has been performed exploiting the setup of a previous work [5]. The results in Fig.3 demonstrate a general reduction in distortion induced by the beam directions and PAPR variations for both implemented BA interpolations. The BD-DPD leads to an improvement of approximately 5dB and 10dB in terms of ACPR for the cubic and spline BA, respectively, as shown in Figs.3a-b. Additionally, the improvement in terms of EVM is approximately 5dB for both methods, as demonstrated in Figs.3c-d

IV. IMPACT STATEMENT AND CAREER PLANS

Thanks to the MTT-S Graduate Fellowship, I was able to broaden my PhD research by exploring different applications of the core concept. With the fellowship's support, I explored multiple research avenues and obtained noteworthy results that culminated in presentations at IMS 2022 and 2023, which have been highly rewarding and have contributed significantly to my personal and professional growth.

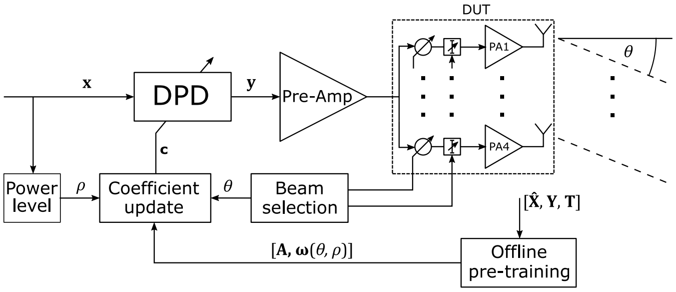

Fig. 2. Block diagram of the adopted DPD configuration for active beamforming arrays.

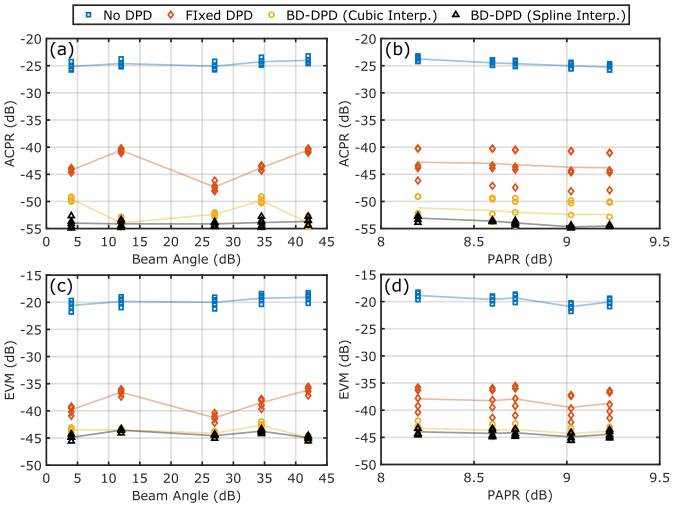

Fig. 3. DPD performance comparison. (a) ACPR and (c) EVM in the validation points plotted across beam angle. (b) ACPR and (d) EVM in the validation points plotted across PAPR. The continuous line indicates the average value in a given DPD configuration across all tested operating conditions.

As I approach the end of my PhD, I am actively considering various options for my future career plans. My ultimate goal is to continue pursuing research in my field, whether in academia or research institutions.

REFERENCES

[1] M. Mengozzi, G. P. Gibiino, A. M. Angelotti, A. Santarelli, C. Florian, and P. Colantonio, "Automatic optimization of input split and bias voltage in digitally controlled dual-input doherty rf pas," *Energies*, vol. 15, no. 13, p. 4892, 2022.

[2] M. Mengozzi, G. P. Gibiino, A. M. Angelotti, C. Florian, and A. Santarelli, "Beam-dependent active array linearization by global feature-based machine learning," in *to be presented at IMS 2023*, 2023.

[3] 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.

[4] Y. Li, X. Wang, and A. Zhu, "Complexity-reduced model adaptation for digital predistortion of RF power amplifiers with pretraining-based feature extraction," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 3, pp. 1780–1790, 2021.

[5] M. Mengozzi, G. P. Gibiino, A. M. Angelotti, C. Florian, and A. Santarelli, "Over-the-air digital predistortion of 5g fr2 beamformer array by exploiting linear response compensation," in *2022 IEEE/MTT-S International Microwave Symposium-IMS 2022*. IEEE, 2022, pp. 394–397.