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A New Frontier for Power Amplifier enabled by Machine Learning

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Abstract

This article focuses on the recent studies of introducing machine learning techniques for radio frequency power amplifiers online operational conditions optimization, primarily at sub6GHz frequency of 5G. We report two demonstrators of advanced power amplifier architecture designed with cutting edge 0.15um-gallium nitride (GaN) HEMT technology, namely: a digital Doherty power amplifier (DDPA) and a novel digitally assisted ultra-wideband mixed mode dual-input power amplifier based on frequency-periodic load modulation (FPLM). For both applications, compact data-driven ML techniques have been applied to boost power amplifiers performance significantly. It is attempted to bring another approach for RF engineers for dealing with sophisticated power amplifiers design and operating tasks.

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Title: **A New Frontier for Power Amplifier enabled by Machine Learning**

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A New Frontier for Power Amplifier enabled by Machine Learning

— *unleashing the full potential of advanced PA with data driven optimization*

Artificial intelligence (AI) and machine learning (ML) technologies are nowadays pervasive in our daily life empowering from smart speaker to thermostat, from self-driving car to robot, and from social network to banking system. In wireless communications, machine learning is being applied in recent years across all layers including network planning, spectrum sensing, channel modeling, security, and needless to mention, all the smart applications running on our mobile devices. Meanwhile, one is envisioning a communication system to bring the hyper-connected experience to every corner of life for beyond 5G and 6G [1]. Application and deployment of AI technology for next generation wireless communications has the profound potential to improve the end-to-end experience and reduce both the CAPEX and OPEX of networks [2]. AI becomes a necessary tool to deliver reliable and versatile services to connect hundreds of billions of machines and humans.

Improving radio hardware performance of radio access network (RAN), particularly, RF power amplifiers, has been a long-lasting challenge with ever-increasing system demand. In the past decades, RF engineers have spent numerous efforts to enhance power amplifier's figure of merits such as efficiency, gain, bandwidth, and linearity. They came up with many brilliant solutions. Nevertheless, as the complexities of advanced power amplifiers circuits, modules and systems keep increasing, it becomes even more challenging and time consuming to design, operate, and optimize power amplifiers for highly dynamic operating, traffic conditions, and radio environment such as massive-MIMO. Such use cases are however very common for nowadays cellular applications.

This article focuses on the recent studies of introducing machine learning techniques for radio frequency power amplifiers online operational conditions optimization, primarily at sub-6GHz frequency of 5G. We report two demonstrators of advanced power amplifier architecture designed with cutting edge 0.15μm-gallium nitride (GaN) HEMT technology, namely: a digital Doherty power amplifier (DDPA) and a novel digitally assisted ultra-wideband mixed mode dual-input power amplifier based on frequency-periodic load modulation (FPLM). For both applications, compact data-driven ML techniques have been applied to boost power amplifiers performance significantly. It is attempted to bring another approach for RF engineers for dealing with sophisticated power amplifiers design and operating tasks.

• From Digital to Intelligent Doherty PA

Doherty power amplifier has been the workhorse for cellular base station radio transmitters [3] thanks to its relatively simple topology with competitive average power efficiency for amplifying signals with high peak-to-average power ratio (PAPR> 6dB). Due to its analog nature, Doherty PA still suffers from several key limitations such as non-optimal power splitting ratio, phase alignment, and Peaking amplifier turning-ON over a wide RF bands and input power levels.

To overcome such challenges, various means including Advanced Doherty Alignment module (ADAM) and Digital Doherty PA (DDPA) were proposed by eliminating the conventional analog based power splitting circuitry (i.e., Wilkinson divider). Instead, one is feeding dual-input RF signals directly to Carrier amplifier and Peaking amplifiers of Doherty PA[4], [5] respectively. Hence, one is able to independently control input signals amplitudes and phases, with excellent results being reported. Figure 1 provides a comparison of a Doherty power amplifier and modified version of it as Dual-input digital Doherty PA highlighting the change.

Multi-input Doherty PA can be digitally controlled by either following a set of derived closed-form equations, which approximates a pre-determined static power splitting ratio and phase imbalance between Carrier and Peaking amplifies, or by offline brute force search and finding satisfying input signal conditions for high efficiency or high output power [5], [6], [7]. However, these methods have several limitations in practice: (1) derived mathematical equations only providing approximation of highly non-linear relationship within PA (i.e., using arctan function), (2) bias voltages optimization not included but critical, and (3) open-loop implementation without capturing the device-to-device variation or operating condition changes (i.e., ambient temperature). Consequently, manual tuning is still required to account for the dynamics of real systems and condition variations. Because of the large searching space of variables, brute force appears to be inefficient for real implementation.

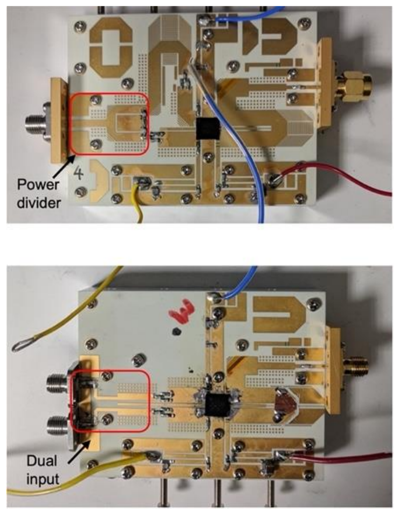

Figure 1. A wideband Doherty power amplifier [8] and its modified version for dual-input Doherty power amplifier operation. The modified part of input power divider is highlighted within the rectangular.

Very recently, there have been several new machine learning data driven online optimization methods proposed and demonstrated. As an initial study shown by simulation [9], Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm was applied to optimize input power splitting ratio, phase offset, and gate bias voltages at the same time for Carrier and Peaking amplifier of a dual input Doherty PA based on ADS and SystemVue softwares. The algorithm is shown below:

Algorithm 1 SPSA based optimization of digital DPA

Input: $\theta = [Vgs_m, Vgs_p, \phi, \alpha]$; % *Initial control parameters*
Input: $\theta_L = [Vgs_{mL}, Vgs_{p,L}, \phi_L, \alpha_L]$; % *Lower bound*
Input: $\theta_U = [Vgs_{mU}, Vgs_{p,U}, \phi_U, \alpha_U]$; % *Upper bound*
Input: c, λ_0 γ *and* γ_1; % *perturbation parameters*
Output: θ^* % *Optimal control parameters*

while *adaptation==True* **do**
  while *converge==False* **do**
    $k{+}{+}$
    clip θ between θ_L and θ_U
    $c_k = \frac{c}{k\gamma}$
    $\lambda_k = \frac{\lambda}{(\lambda_0+k)^\alpha}$
    $\Delta = Bernouli(1, p)$; % *Bernouli perturbation*
    $\theta_+ = theta + c_k \cdot \Delta$; % *+ve perturbation*
    $\theta_- = theta - c_k \cdot \Delta$; % *-ve perturbation*
    Determine $C(\theta_-)$ and $C(\theta_+)$
    Calculate: $g = \frac{(C(\theta_+)-C(\theta_-))}{2 \cdot c_k \cdot \Delta}$
    Update: $\theta = \theta - \lambda_k \cdot g$
  end while
  Obtain optimal control parameter, θ^*
end while

It formulates digital Doherty power amplifier (DPA) real-time optimization as an adaptive online control problem by searching for an optimum solution of a user defined cost function consisting of several power amplifier's figure of merits (a weighted sum of power, gain, efficiency, and linearity etc.), as depicted by Figure 2. Different hyper parameters and initial conditions of optimization was tested. As a result, for instance, optimal points of power added efficiency can be found between 60% to 70% with a great number of close local minimums points.

A further development with lab test bench (shown in Figure 3) for proof-of-concept and engineering demonstration was reported in [10].

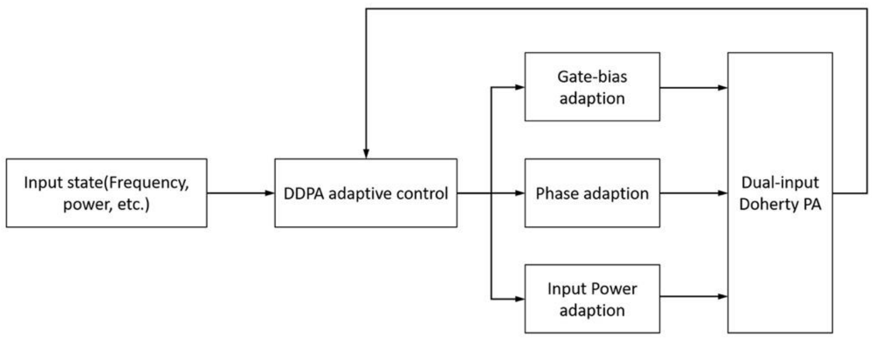

Figure 2. online optimization of Dual-input Doherty PA (DDPA) [10].

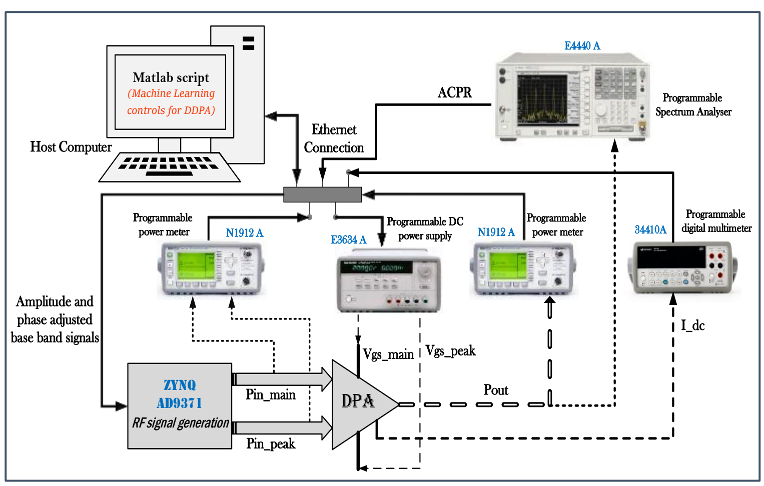

Figure 3. Lab testbench of dual-input digital Doherty PA (DDPA) using machine learning online optimization [10].

One implemented a model-free optimization method with simulated annealing (SA) and extremum seeking (ES), as shown in Figure 4. Its details can be found in [10] The combination of SA and ES makes the system optimization efficient, where SA captures the random and abrupt variation in the system mainly due to frequency and input power level variations, whereas ES captures slow variation in the model such as temperature.

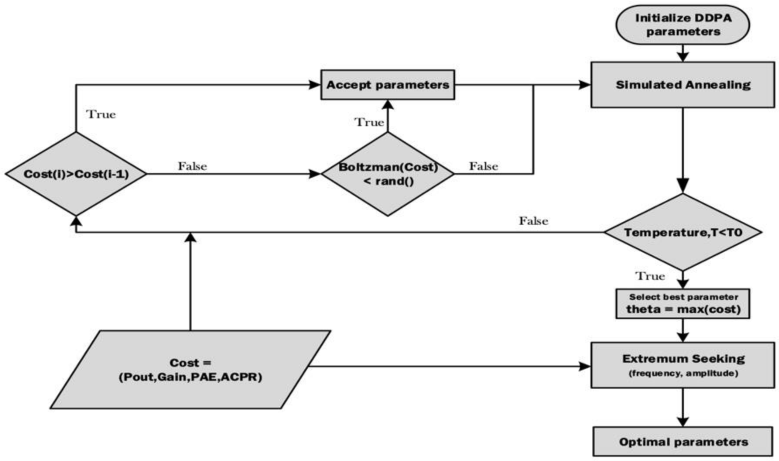

Figure 4. Model-free machine learning algorithm used for DDPA optimization [10]

It should be pointed out that the compactness of machine learning algorithm adopted here is quite different from the general deep learning ML category, such as DNN (deep neural network) in the sense that it neither requires massive training data nor powerful computation power and memory. This is an important feature for efficient implementation of RF applications. Figure 5 shows DDPA online auto-tuning of performance including output power, gain, power added efficiency (PAE) via adaptive control of gate bias voltages (Vg_main, Vg_peak), and input power splitting ratio (α: how much power distributed to Peaking amplifier from total input) and phase imbalance ($\Delta\Phi$) using SA and ES. The optimization goal is to search for an optimal control parameters θ^* maximizing cost function $Q(\theta)$, which is a expressed as weighted sum of PA performance of interest: $\theta^* = argmaxQ(\theta), \theta \in U$, where θ is a vector of the amplifier tuning parameters defined as $\theta = [Vg\_main, \ Vg\_peak, \Delta\Phi, \alpha]$.

As shown in Figure 5, it takes approxmately 40 iterations for SA to perform random exploration with fast convergence. It is then followed by ES algorithm for fine tuning to account for effects such as temperature changes. The program is running on Matlab on a PC using the measurement setup depicted in Figure 3. Significant performance enhancemet in DDPA over a wider frequency range and different input power range (in particular lower input power range) has been observed compared with single input conventional DPA thanks to the auto-tuning procedure, approximately over 15% efficiency boost and 2-3dB gain without using digital predistortion. The algorithm is also able to figure out a reasonable tradeoff among these conflicting PA performance targets by assigning different weights in $Q(\theta)$. It has to be mentioned that dedicated digital predistortion (DPD) schemes was not yet used in [10].

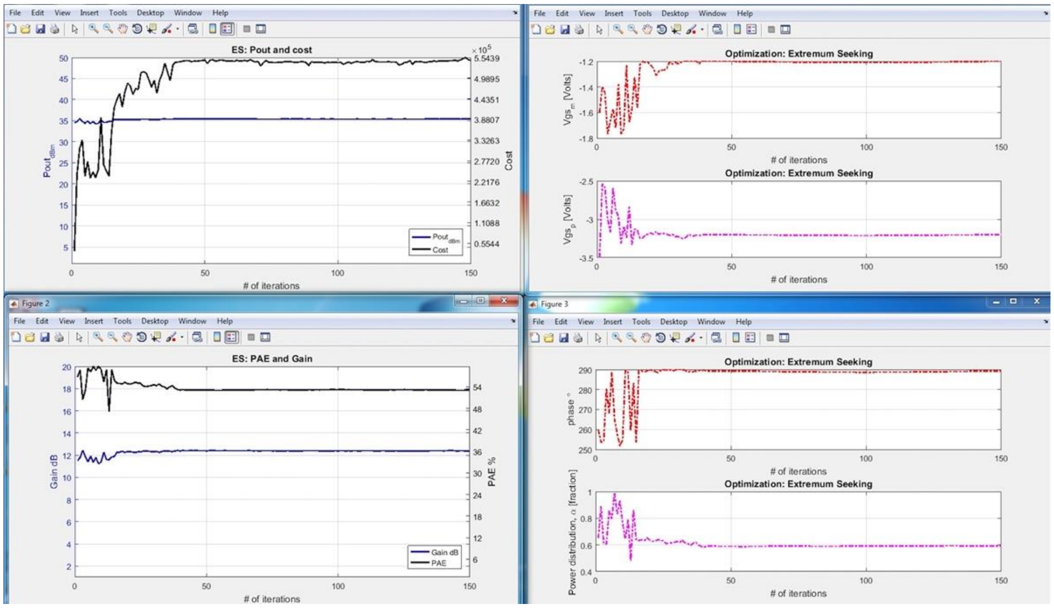

Figure 5. DDPA performance with online auto-tuning of control parameter: Pout and defined cost function (upper left), gate bias voltages for main and peaking amplifier (upper right), PAE and Gain (lower left), and input phase imbalance and power splitting ratio (lower right). The overall goal is to maximize the user defined cost function Q(θ).

• Digitally Assisted Frequency-Periodic Load Modulation PA

Doherty power amplifier in practice is still limited in terms of RF bandwidth, due to many factors such as device patristics, power combiner and phase alignment challenges. A novel mixed mode ultra-wideband frequency-periodic load modulation (FPLM) PA is proposed to achieve high performance over multiple contiguous frequency bands, enabled by a digitally assisted dual-input configurations of AI module. It provides automatically optimum signal combination, magnitude and phase of dual-input signals. Figure 6 illustrates the several types of load modulations, such as a virtual open stub Doherty, outphasing, general Doherty, and anti-phasing outphasing spanned over a three times RF frequency range ($0.5f_0$~$1.5f_0$, f_0 denotes the design center frequency). Quite distinct and proper input signal's amplitude and phase relationships are necessary for this amplifier to behave as Doherty and Outphasing operation modes over five different frequency ranges.

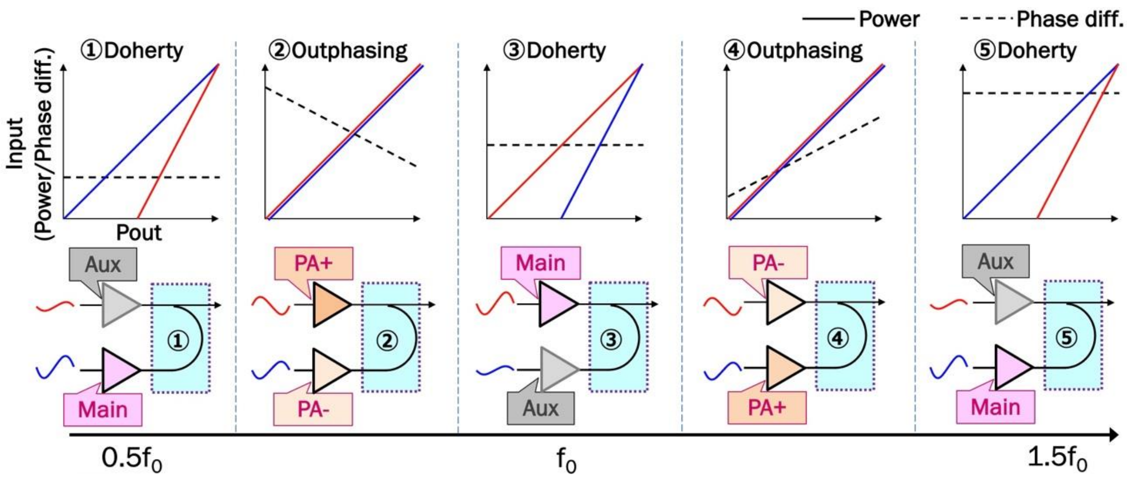

Figure 6. Concept of a frequency-periodic load modulated (FPLM) PA with controlled dual input signal over frequency, and f0 being the center frequency.

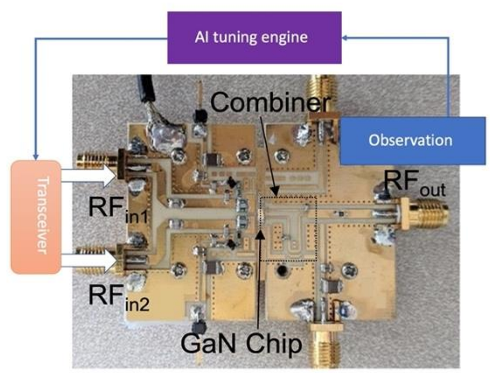

Figure 7. Prototyped dual-input FPLM GaN PA under AI digitally assisted operation.

A novel output combiner was proposed by absorbing devices capacitances into part of the equivalent transmissions and providing differently desired output power combining functions for above mentioned five frequency ranges, respectively. The design detailed can be found in [11]

Figure 7 shows the built FPLM GaN PA prototype consisting of two bare die chips with 0.15-µm HEMTs. Similar AI algorithms shown in Figure 4 have been adopted to auto tuning the two RF input signals amplitude and phases based on a user-defined cost function. The bias voltages of these two HEMTs were at pinch-off and not tuned during the optimizations. Without manually interaction and specifying the specific PA operation modes, AI module is able to autotune the dual-channel transceivers parameters on the fly and achieves desired PA modes with high efficiency. Figure 8 shows the measured FPLM PA average efficiency (6dB back-off) over the whole bands.

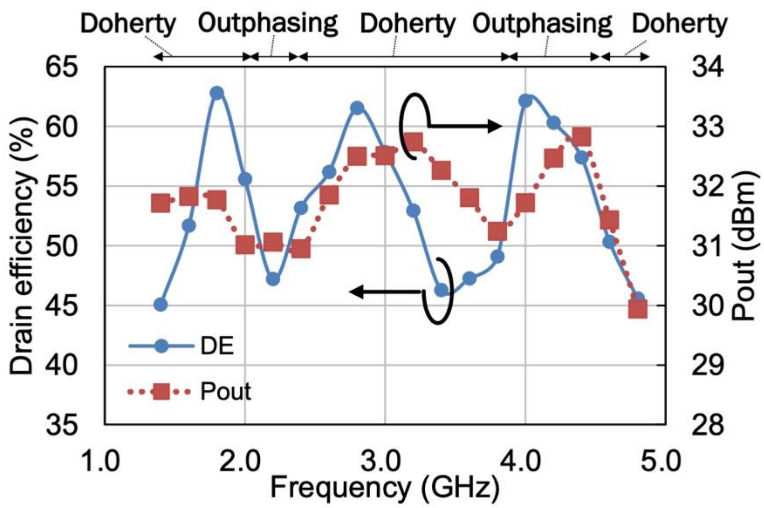

Figure 8. Measurement of the prototyped dual-input (FPLM) PA [11].

A detailed analysis of the operating mode at each frequency range is omitted here but can be found in [11]. Digital assistance is able to fully utilize the FPLM PA's design potential and handle' its sophisticated control and optimization and offering the state-of-the-art efficiency performance over 110% fractional bandwidths, as compared in Table 1.

Table 1. Comparison of sub-6GHz high efficiency wideband amplifiers.

Ref.	Year	Freq (GHz)	Fractional BW (%)	Efficiency (%)	Pout (dBm)	Configuration	Backoff
[12]	2012	3.0-3.6	18	38-56	37-38	Doherty	6dB(CW)
[7]	2013	1.0-3.0	100	48-68	37.1-38.9	Doherty-Outphasing	6dB(CW)
[13]	2017	0.9-2.15	82	32.-36	30.0-30.7	Envelope Tracking	6dB (CW)
This work [11]	2019	1.4-4.8	110	45-62	29.9-32.8	FPLM PA	6dB (CW)

• Outlook

The reported applications shows that compact data-driven AI techniques can help to unleash the full potential of novel high performance power amplifier for flexible and wideband wireless applications. Integrating cutting edge semiconductor device technology (GaN), circuit design innovation, and artificial intelligence (digital assisted auto-tuning together with digital front-end (DFE) including digital predistortion [14]) will facilitate a solution of agile and superior RF front end. It is worthy to point out that the proposed methodology is not only applicable for cellular transmitter, but also for general applications (such as RF industrial heating), in which radio frequency hardware/amplifiers is the key dominating the system-level performance.

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Reference

[1]. 6G Vision Whitepaper, The Next Hyper Connected Experience for All, Issued by Samsung Research, Whitepaper, July 2020.

[2]. X. Zhou, *et al.*, “Intelligent Wireless Communications Enabled by Cognitive Radio and Machine Learning,” in *China Communications,* pp. 16-48. December 2018.

[3]. F. H. Raab *et al*., "Power amplifiers and transmitters for RF and microwave," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 50, no. 3, pp. 814-826, March 2002,

[4]. A. Ahmed *et al*., "Line-up efficiency improvement using dual path Doherty power amplifier," *2013 European Microwave Conference*, Nuremberg, 2013, pp. 275-278.

[5]. R. Darraji *et al*., “Doherty Goes Digital: Digitally Enhanced Doherty Power Amplifiers," in *IEEE Microwave Magazine*, vol. 17, no. 8, pp. 41-51, Aug. 2016.

[6]. R. Darraji and F. M. Ghannouchi, "Digital Doherty Amplifier with Enhanced Efficiency and Extended Range," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 11, pp. 2898-2909, Nov. 2011.

[7]. C. M. Andersson *et al*., "A 1–3-GHz Digitally Controlled Dual-RF Input Power-Amplifier Design Based on a Doherty-Outphasing Continuum Analysis," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 61, no. 10, pp. 3743-3752, Oct. 2013.

[8]. Y. Komatsuzaki *et al*., "3.0–3.6 GHz wideband, over 46% average efficiency GaN Doherty power amplifier with frequency dependency compensating circuits," *2017 IEEE Topical Conference on RF/Microwave Power Amplifiers for Radio and Wireless Applications (PAWR)*, Phoenix, AZ, 2017, pp. 22-24.

[9]. S. Niu *et al*., "Stochastically approximated multi objective optimization of dual input digital Doherty Power Amplifier," *2017 IEEE 10th International Workshop on Computational Intelligence and Applications (IWCIA)*, Hiroshima, 2017, pp. 147-152.

[10]. R. Ma *et al*., "Machine-Learning Based Digital Doherty Power Amplifier," *2018 IEEE International Symposium on Radio-Frequency Integration Technology (RFIT)*, Melbourne, VIC, 2018, pp. 1-3.

[11]. Y. Komatsuzaki *et al*., "A Novel 1.4-4.8 GHz Ultra-Wideband, over 45% High Efficiency Digitally Assisted Frequency-Periodic Load Modulated Amplifier," *2019 IEEE MTT-S International Microwave Symposium (IMS)*, Boston, MA, USA, 2019, pp. 706-709.

[12]. J. M. Rubio *et al*., "3–3.6-GHz Wideband GaN Doherty Power Amplifier Exploiting Output Compensation Stages," in *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 8, pp. 2543-2548, Aug. 2012.

[13]. S. Sakata *et al*., "An 80MHz modulation bandwidth high efficiency multi-band envelope-tracking power amplifier using GaN single-phase buck-converter," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, Honolulu, HI, 2017, pp. 1854-1857.

[14]. M. Mengozzi *et al.*, “A. GaN Power Amplifier Digital Predistortion by Multi-Objective Optimization for Maximum RF Output Power,” *Electronics*, 2021, *10*, 244.