# Energy-Efficient, Wideband, and Linear PA Theory and Architectures for Next-Generation Transmitters

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***Abstract*—This paper summarizes the proposed theory, design, and novel power amplifier (PA) architectures aimed at achieving energy-efficient, wideband, and linear operations. We have successfully demonstrated various PA prototype circuits using advanced Gallium Nitride (GaN) and silicon processes for 5G Sub-6 GHz and mmWave bands (FR1 and FR2), as well as the potential 6G cmWave bands (FR3).**

***Index Terms*—CMOS, CLMA, Doherty, energy efficiency, GaN MMIC, load modulation, power amplifier, RF-DAC, and RFIC.**

## I. INTRODUCTION

THE increasing demand for mobile data traffic has introduced significant challenges and new requirements for the development of beyond 5G and 6G communications. In the rapidly advancing field of wireless communication and sensing systems, research highlights the substantial potential of higher frequency bands and multiple active antenna systems to enhance wireless data throughput. However, these systems face issues related to energy efficiency, bandwidth, and nonlinearity, leading to considerable heat dissipation, complex integration processes, high costs, and reliability concerns. These challenges are particularly pronounced at centimeter-wave (cmWave) and millimeter-wave (mmWave) frequencies, where the power amplifiers (PA), govern many performance aspects of the wireless link. In radio base stations, mobile handsets, and wireless point-to-point (PTP) links, the energy efficiency, bandwidth, and linearity performance of the PA are critical for maximizing channel capacity, reducing operational costs, and enhancing integration [1].

This project aims to address the fundamental design challenges of PAs by proposing innovative architectures and design theories that excel in efficiency, bandwidth, and linearity. The proposed theories and designs are intended to be compatible with wideband communication signals and complex modulation schemes in active antenna array systems. In this report, we have successfully demonstrated various PA prototype circuits in advanced Gallium Nitride (GaN) and silicon processes for 5G Sub-6 GHz and mmWave bands (FR1 and FR2), as well as the potential 6G cmWave bands (FR3).

## II. PROJECT OUTCOME

### A. Generic Theory and Design Methodology

We have proposed a generic three-port combiner synthesis theory and design approach that serves as a theoretical basis for analyzing and understanding all existing three-way high-efficiency PA architectures with various operation modes [2]. This analytical approach enables the determination of network parameters for the output combiner based on the current and voltage drive profiles of the sub-amplifiers and predefined boundary conditions. As illustrated in Fig. 1, we designed and fabricated a 2.14 GHz 30-W three-way Doherty PA using identical GaN HEMT transistors. The prototype PA

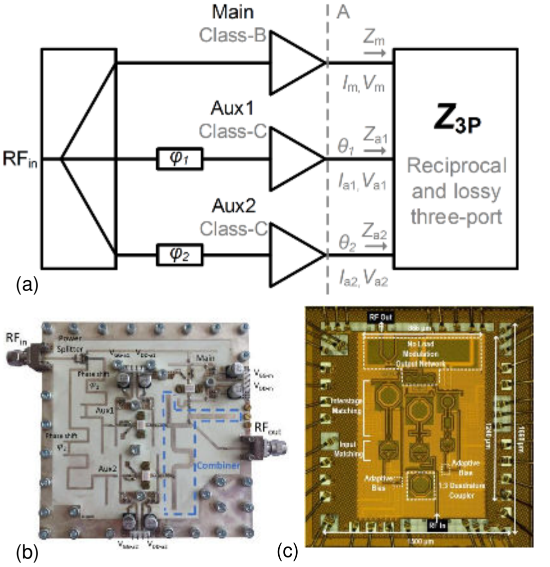

Fig. 1. (a) Block diagram of the generalized three-port combiner used for the analysis of three-way PAs [2]. (b) The three-way GaN HEMT Doherty PA prototype circuit for Sub-6 GHz applications and (c) the three-way CMOS high-efficiency PA for mmWave applications [3].

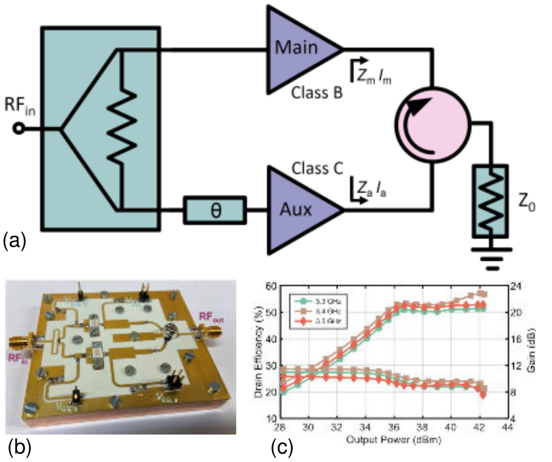

Fig. 2. (a) Block diagram of the RF-input circulator load modulated amplifier (CLMA). (b) The fabricated proof-of-concept GaN HEMT prototype circuit, and (c) corresponding large signal performance.

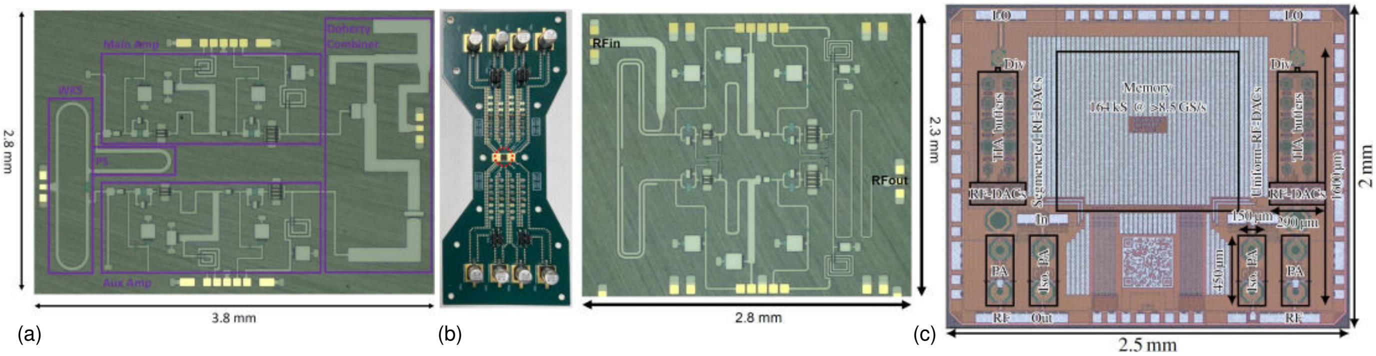

Fig. 3. (a) Doherty [4] and (b) push-pull [5] PA prototype circuits in MMIC GaN on SiC process, and (c) the RF-DAC-based transmitter [6] in 22 nm FDSOI CMOS process for 6G FR3 cmWave applications.

can linearly transmit OFDM signals with 8.5- and 11.5-dB PAPR, achieving average efficiencies of $56.6\%$ and $46.8\%$ at average output power levels of $36.8$ dBm and $33.8$ dBm, respectively. Furthermore, we proposed and implemented a mm-Wave three-way PA topology in a 45 nm RFSOI CMOS process, which avoids the trade-off between bandwidth and load modulation. This topology enhances efficiency at back-off power levels without relying on load modulation [3]. Utilizing a $100$ MHz 5G NR FR2 1-CC 64-QAM signal, the prototype PA achieves average power and PAE of $6.45-12.61$ dBm and $5.9-16.4\%$ from $25-40$ GHz, respectively.

### B. Innovative PA Architecture

We have also proposed a novel active load-modulated PA architecture, referred to as the circulator load modulated amplifier (CLMA) [7], [8]. In its most simplified form, the CLMA architecture comprises a class-B biased main amplifier, an auxiliary amplifier biased in class-C mode, and a circulator-based output combiner network. With correct driving conditions, the CLMA can operate in a manner similar to Doherty PA or sequential PA architectures. As shown in Fig. 2, experimental verification demonstrates that the CLMA architecture can achieve back-off efficiency enhancement using a non-reciprocal output combiner for the first time.

### C. PA Prototype Circuits for 6G Applications

In the advancement towards 6G communications, the FR3 centimeter-wave (cmWave) frequency band ($7-24$ GHz) is crucial for its balanced transmission capacity and coverage area. Spectra within the FR3 band, such as $10.7-13.25$ GHz and $14-15.35$ GHz, have been identified by the International Mobile Telecommunications (IMT) consortium as vital for future developments. Consequently, we have designed various PA prototype circuits using a $150$ nm GaN on SiC process and a $22$ nm FDSOI CMOS process. As shown in Fig. 3, we demonstrate a $11.0-17.5$ GHz GaN on SiC MMIC push-pull PA with an innovative input balun for impedance matching, an output balun to counteract transistor parasitics for enhanced bandwidth and compactness, and cross-coupled neutralization networks with interdigitated and metal-insulator-metal (MIM) capacitors to boost stability and gain [5]. Experimental results exhibit a peak PAE of $18\%-34\%$ with an output power of $34.0-36.5$ dBm within the design frequencies. Additionally, we designed a $10-14$ GHz Doherty PA with continuous-mode (CM) operations to extend bandwidth [4]. The circuit exhibits a peak PAE of $28\%-38\%$ and back-off PAE of $21\%-31\%$, with an output power higher than $34$ dBm across the operating frequencies. We also present an RF-DAC-based transmitter that uses an expanding characteristic to linearize the PA [6]. Implemented in 22 nm FDSOI CMOS, the transmitter operates with a carrier frequency of $12.5$ GHz, achieving a sample rate of $7$ GS/s. Measurements with 64-QAM OFDM signals show $\mathrm{EVM_{RMS}}$ and ACPR lower than $5.75\%$ and ACPR $-32.2$ dBc when using the RF-DAC-based predistortion.

## III. CAREER PLAN AND IMPACT STATEMENT

I am deeply honored to receive the MTT-S Graduate Fellowship Award and excited to explore the vast potential of next-generation wireless communication systems. I am enthusiastic about applying the knowledge, skills, and insights gained from this fellowship to advance wireless communication and sensing applications in both academia and industry. Furthermore, I am eager to collaborate closely with MTT-S and engage with experts in the field to make meaningful contributions.

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