



ADDIS ABABA UNIVERSITY

Addis Ababa Institute of Technology (AAIT)
School of Electrical and Computer Engineering
Communication Engineering Graduate Program

**A Comparative Analysis of Power Amplifier Types in
Massive MIMO Systems for 5G Networks.**

by

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with Part of the MSc in Communication Engineering Requirement

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Declaration

This thesis, "A Comparative Analysis of Power Amplifier Types in Massive MIMO Systems for 5G Networks," is an original work that I, Gamachu Tafari, hereby declare fulfills one of the prerequisite for AAiT in the MSc In Communication Engineering Program. I attest that every source used in this thesis has been properly cited and that no portion of it has ever been submitted for credit toward a degree or other qualification at this university or any other.

Name of the Student

Signature

Date

This thesis has been submitted for examination with my approval as a university advisor.

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Signature

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Addis Ababa, Ethiopia

Abstract

Class AB, Doherty, and Envelope Tracking Power Amplifiers (ETPA) are the three types of power amplifiers that are thoroughly compared in this thesis in the context of 5G networks. Current communication standards require power amplifiers to achieve high efficiency over increasingly larger dynamic ranges and bandwidths while maintaining strict linearity criteria. The study uses key criteria like power-added efficiency, linearity, gain, and output power to evaluate their performance. Simulations were conducted using MATLAB and the Advanced Design System to evaluate amplifier properties under various settings, including the use of Digital Pre-Distortion to improve nonlinearity. The results showed that Class AB amplifiers achieved PAE of 51.090 % and improved AMAM Conversion. Excellent back-off efficiency and significant advantages in high-power scenarios are exhibited by Doherty amplifiers, especially when DPD integration is employed for enhanced linearity. Despite achieving 70% PAE and demonstrating superior efficiency over a broad dynamic range, envelope tracking amplifiers require complex design due to their reliance on dynamic voltage control. By balancing the trade-offs between linearity and efficiency, this study determines the optimal amplifier topologies for 5G networks that are both high-performance and energy-efficient. These discoveries contribute to the advancement of the technology by revealing the future applications of power amplifiers in wireless communication systems.

Key Words

Envelope Tracking PA; Doherty PA; Fifth generation; efficiency; Gain; linearity; Output Power; Digital Pre-Distortion; massive MIMO; Power Amplifiers.

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List of Acronyms

DPA: Doherty Power Amplifier

ETPA: Envelope Tracking Power Amplifier

PAE: Power Added Efficiency

MIMO: Multiple-Input Multiple-Output

5G: Fifth Generation

EE: Energy efficiency

PA: Power Amplifier

RF: Radio frequency

DPD: Digital Pre-Distortion

MER: Modulation Error Ratio

Chapter 1

Introduction

1.1 Background and motivation

The creation of effective and high-performance power amplifiers becomes essential as the need for wireless communication keeps increasing. This is so because in wireless systems, power amplifiers are in charge of increasing signal strength and guaranteeing dependable connection [1]. Various categories of power amplifiers are frequently employed in wireless communication systems, such as Class AB, Doherty, and Envelope Tracking amplifiers [2]. Each of these power amplifier types has its advantages and disadvantages, which need to be carefully considered in the context of 5G MIMO systems. In a comparative analysis of these power amplifier types for 5G Networks, several factors need to be considered. These factors include power efficiency, linearity, output power, and Gain of implementation. Additionally, the specific requirements and constraints of a 5G Network, such as high data transmission capacity, low latency, and energy efficiency, should be taken into account. To conduct a comparative analysis, several sources can be used [3]. In the framework of 5G networks, these sources offer understanding of the design, performance, and efficiency of many power amplifier models. cm-wave power amplifier developments for 5G systems and comparisons of various circuit designs, device technologies, and efficiency-boosting strategies [4] [5].

The major goal of this investigation is to determine the appropriateness of Class AB, Doherty Power Amplifier, and Envelope Tracking Power amplifiers for use in 5G networks; by considering that factors such as efficiency, linearity, power consumption, cost, and complexity. By comparing these three amplifier types, we aim to provide insights into their respective strengths and limitations, enabling network designers and engineers to make informed deci-

sions regarding power amplifier selection and optimization. In the following sections, we will first delve into the Power Amplifiers Concept. We will then characteristics, and See the applications of Class AB, Doherty and Envelope Track Power Amplifiers. after that the significance of PAs in 5G applications, Increased efficiency, and Linearity of power amplifiers will be discussed. Comparative Analysis Subsequently, we will conduct a comprehensive comparative analysis of these amplifier types, evaluating their performance based on predefined criteria. Also, each of these amplifier types has its advantages and disadvantages, and extensive research is being conducted to determine the best option for 5G Network systems regarding power linearity, PAE, and overall system performance. the analysis will be backed by simulations, experimental results, and references to existing studies in the field. By examining the performance differences between Class AB, Doherty, and ET power amplifiers, this paper aims to contribute valuable insights for the advancement of power amplifier technology in the context of emerging 5G networks. Finally, this research will help with the improvement of power amplifier designs, resulting in increased efficiency, lower costs, and better overall performance in future wireless communication systems.

1.1.1 Statement of the problem

The deployment of 5G networks requires power amplifiers that can operate effectively across high frequencies and wide bandwidths. However, achieving great efficiency frequently conflicts with maintaining linearity, a critical need for handling the several modulation schemes involved in 5G communication. The requirement to manage high Peak-to-Average Power Ratios in communication systems, especially in 5G and beyond, has grown dramatically with the development of sophisticated modulation methods like Orthogonal Frequency Division Multiplexing and Quadrature Amplitude Modulation. 5G waveforms are comparable to 4G/WLAN and have a high PAPR; they will inevitably lower a PA's power back-of efficiency and considerably degrade its average PAE. In order to increase performance, linearity, and efficiency in 5G networks, it is necessary to thoroughly compare the advantages and disadvantages of each type of radio frequency amplifier. The problem is figuring out which type of power amplifier is best for handling 5G Network performance; some may offer higher linearity or efficiency, while others may be better suited for reducing power consumption or cost or Structure Complexity. Choosing the most appropriate power amplifier type for Massive MIMO systems involves taking into account factors like linearity, efficiency, output power, gain, power consumption,

signal distortion, nonlinearity, and interference—all of which may interact differently with the particular requirements and challenges of Massive MIMO.

1.1.2 Objectives

General Objectives

Examining and assessing the potential of DPA, Class-AB, and ET PAs based on their performance metrics for 5G networks are the main goals of this thesis.

Specific Objectives

- **Class-AB Power Amplifier:** Evaluate the efficiency and linearity aspects of the Class-AB PA. Evaluate how Class-AB PA influences interference and signal distortion.
- **Doherty Power Amplifier:** - Assess the Doherty PA's efficiency gain in comparison to Class AB PA. Examine the Doherty PA's PAE and bandwidth increase for 5G communication networks. Examine Doherty PA's design and implementation issues in order to integrate it with 5G base stations and devices.
- **Envelope Tracking Power Amplifier:** Evaluate the efficiency advantages attained in 5G networks, especially while operating in a dynamic environment. Examine how Envelope Tracking PA can lower power usage and lengthen battery life.
- **Implications for 5G Networks:-** Analyze how Digital Predistortion will improve non-linearity for Doherty PAs in 5G network performance.

1.1.3 Scope and Limitation

Scope

Class-AB, Doherty, and Envelope Tracking Power Amplifiers are the three power amplifiers whose features and performance matrices will be the focus of the study. It examines each power amplifier's characteristics and effects in 5G networks. It compares the three power Amplifiers' findings for use in 5G networks.

Limitation

We can integrate GaN-based PA, but it is expensive and requires updated ADS to integrate with GaN transistors. In addition, real-world factors like hardware integration challenges and environmental conditions are not taken into account, which could affect amplifier performance in real-world applications. These factors are among the limited types of advanced transistors used in PA.

1.1.4 Structure of the thesis and its Contributions

The Format of the research

This thesis paper is organized as follows: Chapter one covers the introduction of the research, along with a survey of relevant literature on the subject, problem statements, research objectives, and scope; Chapter Two describes the experimental setup and data collection methods; Chapter Three discusses the linearity of power amplifiers for 5G networks, efficiency enhancement, and the role of digital pre-distortion techniques in improving PA performance; additionally Chapter three covers the three types of power amplifiers in 5G networks, massive MIMO, and power amplifiers. We next examine these findings in Chapter Four after presenting the results of our investigation. The research findings are then contrasted with the performance of PA used in 5G. In Chapter Five, we conclude with a summary of our key conclusions and suggestions for further research.

Contributions of the thesis

The main work would focus on demonstrating significant improvements in Energy efficiency by Analyzing power consumption in 5G Networks by Evaluating The performance Metrics of Selected PA's. and a linearity enhancement by Ensuring minimal signal distortion under varying conditions, which is critical for 5G applications.

Comprehensive comparative analysis: To assess the viability of three power amplifier types for 5G massive MIMO systems, a thorough comparison of Class AB, Doherty, and Envelope Tracking Power Amplifiers was carried out. Key performance indicators like as output power, efficiency, linearity, and gain were all examined.

Simulation-Based Insights:The performance of the chosen amplifiers was modeled under various operating conditions using MATLAB and the Advanced Design System. showed how

Digital Pre-Distortion may enhance the linearity and efficiency of Doherty Power Amplifiers, offering helpful insights into linearization techniques for 5G systems.

Performance Metrics Evaluation: The efficiency and linearity trade-offs of each power amplifier type were assessed and quantified, highlighting the distinct advantages and disadvantages of each under a variety of operating conditions.

5G System Optimization Guidelines: Highlighted the functions of particular amplifiers in improving system performance in situations requiring high efficiency, wide bandwidth, and low distortion, and offered helpful suggestions for choosing and optimizing power amplifiers based on 5G network requirements, including power consumption, cost, complexity, and integration challenges.

1.1.5 Literature Review

In paper, [3] At 3.6 GHz, the authors evaluate two power amplifier topologies that are built using lumped components: a traditional DPA and an OPA. An OFDM-modulated signal with 7.5 dB PAPR was used to test the planned Doherty and Outphasing PAs at 3.6 GHz. With EVM and ACPR levels within the state of the art, the simulations displayed steady behavior. The OPA's efficiency was 58.3% and its saturation power was 33 dBm, whereas the DPA's was 35 dBm and its PAE was 44.2%. Consequently, the DPA attains a greater output power and efficiency; nevertheless, at maximum output power, the DPA's efficiency falls short of the OPA's.

In a paper [6] compares two MMIC PAs, one based on class-AB and the other on Doherty, for microwave backhaul applications. Results show both architectures have similar performance, with the Doherty having slightly higher back-off efficiency. The MMICs have been characterized between 1 and 15 GHz, showing a small signal gain of 11 dB for an AB-PA and 7 dB for a DPA. In large signal conditions, the DPA shows higher efficiency, lower amplitude distortion, and better AM/PM conversion than the AB-PA. At saturation, the DPA has a 50% higher back-off efficiency. A comparison between two power amplifiers, a class-AB, and a Doherty PA, for microwave backhaul applications has been presented. The DPA demonstrated higher efficiency but at the expense of lower linearity and a larger chip area.

In a book [7] We deeply analyzed all concepts of Linearity, Energy efficiency, and other parameters to be compared for our power amplifier. Mathematical modeling of Linearity and energy enhancement is discussed. All classes of amplifier used for this paper is discussed in

this book in detail.

in a paper [8] ADS software is used to create an AB-Class PA in the 2.11-2.17GHz frequency band, and the PdB and TOI measurements are reported and evaluated. Maximum linear output power at 2.11 G is 46.0dBm, for 2.14G is 46.5dBm, and for 2.17G is 46.7dBm.

In paper [9] The talk focuses on constructing power amplifiers utilizing WBET for OFDM applications in WLAN systems such as 802.11g. The goal is to improve efficiency, reduce distortion, and optimize temporal alignment between the baseband and RF pathways in order to satisfy contemporary WLAN specifications for high data rates and spectrum efficiency.

1.1.6 Methodology

When we evaluated RF power amplifiers for comparison purposes; we prepared our methodology as follows.

a. Research Design

- **Objective:** The fundamental objective of this research is to evaluate three types of power amplifiers utilized in huge massive MIMO systems for 5G networks.
- **Approach:** We will conduct a comprehensive analysis by examining their key performance indicators, their performance characteristics, and their suitability for massive MIMO deployments.

b. Data Collection

- **Datasets:** Gather data from existing literature, research papers, and technical specifications of different PA models.
- **Parameters:** Collect key parameters for each PA type, including Output Power, Power Added Efficiency, linearity, and gain.

c. Power Amplifier Types

- **Selection Criteria:** Identify a set of representative PA types that are more energy efficient and have good linearity, commonly used in 5G massive MIMO systems.
- **Types to Compare:** The types of Power Amplifier we are going to compare in this paper is Class AB, Doherty, and Envelope Tracking Power amplifier

d. Performance Metrics

- **Output power:** Maximum power delivered to the load, measured in dBm (decibels relative to 1 milliwatt). Higher output power allows for longer transmission distances or driving larger loads.
- **Efficiency:** Measured as Power Added Efficiency, it denotes the ratio of output power to DC power consumption. A higher PAE is desirable
- **Gain:** Amplification achieved by the circuit, expressed in decibels (dB). Higher gain allows for weaker signals to be amplified
- **Linearity:** How faithfully the amplifier reproduces the input signal without distortion. Measured by metrics like AC Power Ratio or Error Vector Magnitude. Lower distortion are desirable.

e. Experimental Setup

- **Simulation:** we use ADS software (Advanced Design System) to simulate PA behavior. and MATLAB for Analysing the effects of Doherty PA on ACPR and MER results.
- **Model Parameters:** Each of the three power amplifiers operates in a distinct frequency range. In order to analyze the characterization of a power amplifier in a communication system, we choose the Doherty PA, which has a frequency range of 3.6-3.8 GHz and a gain of 29 dB. This makes it appropriate for moderate data rates and greater coverage. Input Signal Types are primarily modulated wideband signals carrying data, control, and synchronization information. The power supply voltage is in the range of 5-12 V.
- **Performance Evaluation:** Run simulations for each PA type and record relevant metrics.

f. Analysis and Comparison

Calculate and compare PAE, linearity, Output power, and, Gain. then Create plots or charts to visualize the differences. At the last Discuss the implications of the findings.

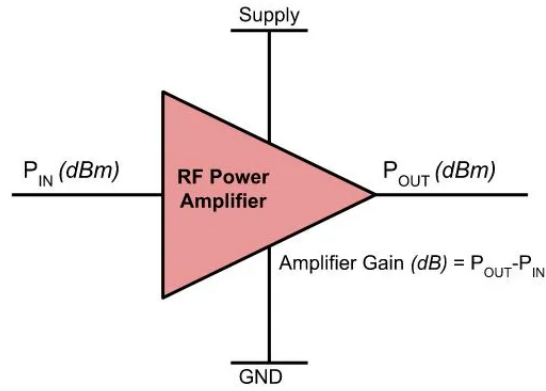


Figure 1.1: An illustration of a radio frequency power amplifier Structure

and provide recommendations for Best use of Massive MIMO at the base station of 5G networks and Draw a Conclusion.

A block schematic of the measuring equipment used to collect data for our three types of PA model study. As we note from the measurement setup in Figure-1 of a block diagram of a Radio Frequency Power Amplifier, we will simply observe the outcome of the three power amplifiers for the provided RF signal [10]. the results of this work will be used to depict Efficiency vs. Output Power, Gain vs. Output Power, and Linearity vs. Output Power.

Chapter 2

Power Amplifier

Few components are as fundamental to the field of electronics as power amplifiers, which increase the amplitude of electrical impulses. These devices enable a wide range of applications, such as audio systems and telecommunications, by converting small input impulses into larger output signals. Power amplifiers are complicated devices, and understanding them necessitates knowledge of the various technologies used in their construction, including Class-A, Class-B, Class-AB, and Class-D configurations. Additionally, there are Wireless communication systems typically employ a range of power amplifier types, including Doherty power amplifier and envelope-tracking power amplifier, the performance of which will be investigated in the future chapter. Practical applications are governed by the particular advantages and trade-offs that each class offers in terms of efficiency, linearity, and heat dissipation. As a result, this analysis will provide a critical viewpoint on power amplifiers, examining their technological developments, working principles, and impact on modern communication infrastructure, particularly in relation to MIMO Systems, underscoring their vital role in the development of 5G networks. Power amplifiers are crucial components of modern communication systems since they significantly affect the overall efficacy and performance of wireless transmission. By modulating and amplifying signals, these devices guarantee that data may be sent over diverse distances while keeping clarity and integrity. Because of the increasing popularity of sophisticated modulation techniques with high Peak-to-Average Power Ratios, power amplifiers that function well even in low-power situations are required. The Switched-Capacitor Power Amplifier (SCPA), for example, is explained in [11]. demon-

strates improved performance by reducing crossover distortion, which improves signal integrity. Additionally, class-B power amplifiers, especially those that use Double-Gate MOSFETs, achieve significant efficiency and linearity, making them compatible with emerging standards like LTE-M [12]. This combination of cutting-edge power amplifier design highlights how essential they are to improving the effectiveness of communication systems and user experience in general. Furthermore, the PA's power back-of-efficiency will inevitably be decreased by this high PAPR, which will also considerably worsen its average PAE. As a result, Doherty PA and Envelope Tracking PA are both regarded to be extremely appealing for enhancing efficiency in 5G PA design.

2.1 Power Amplifier Classis

The classification of power amplifiers is influenced by the transistor's bias, harmonic termination, and operating mode. The development of power amplifiers, particularly in terms of their efficiency and output characteristics, has been a major advancement in the field of electronics. Three of the most popular types of amplifiers for enhancing 5G network performance are class AB, Doherty, and envelope-tracking amplifiers; each is made to meet specific operating requirements. Class AB amplifiers are employed in 5G networks where moderate power levels and a good balance between linearity and efficiency are sought. They function effectively in instances when signal integrity is critical, notably when providing high-quality data and voice communications [13]. However, because the Doherty amplifier architecture employs power supply modulation to boost efficiency at high output levels, it is particularly helpful for wireless transmission. The network can enable high-speed data transfer with less power loss thanks to the Doherty PA's ability to manage the high peak to average power ratios typical of 5G signals. Meanwhile, Envelope Tracking amplifiers maximize RF signal efficiency by employing dynamic power supply techniques, which enhances the performance of modern mobile applications. An envelope tracking technique is used in 5G networks to increase power amplifier performance by reducing power consumption and improving signal quality [14]. In base stations and mobile devices, where power efficiency is crucial, this technique is very helpful. We analyze class AB, Doherty PA, and EVT PA in this thesis. There are more PA classes, but they are not covered in this Paper due to the Scope of the research.

2.1.1 Class AB Power Amplifier

As the name suggests, class AB is biased between classes A and B. Its transmit angle, or transistor conduction angle (the amount of time a transistor is actively conducting current during an input signal cycle), is in the midpoint of that of classes A and B, or 180 degrees to 360 degrees. Between class A and class B, the potential peak efficiency ranges from 50% to 78.5%. Additionally, the linearity performance is similar to that of a class B biased PA. A balance between linearity and efficiency is achieved by Class AB power amplifiers, one of the many amplifier classes, which makes them ideal for a variety of applications, especially in communication systems. These amplifiers reduce distortion and provide greater performance even in a range of signal circumstances by operating in a mode that permits both conduction overlap in the output stage and improved linear response. However, when working with signals that have high peak-to-average power ratios, their efficiency tends to deteriorate at high back-off levels, which might be crucial [15]. However, the Doherty Power Amplifier has improved in this instance. This quality is especially crucial in today's wireless communications, where maintaining linearity while maximizing power efficiency is essential. Class AB amplifiers, while more efficient than Class A types, cannot match the performance of advanced techniques like Doherty and envelope tracking, which have been developed to further enhance amplifier performance under specific operating conditions [16]. Thus, while Class AB amplifiers are foundational in design, the evolution toward more efficient architectures remains paramount in the quest for optimal performance. Class-AB amplifiers should have an efficiency of 55% to 79.53% [17]. The increased efficiency of Class AB amplifiers over Class A amplifiers is one of its main benefits. By biasing the transistors near the cutoff point, Class AB amplifiers operate in a more efficient region, reducing power consumption and heat generation [18]. This efficiency improvement is particularly beneficial for power-hungry applications like 5G, where minimizing energy consumption is crucial. there are Factors for Comparative Analysis; such as Cost, PAE, Complexity, Linearity Output power, and Gain.

Cost: Compared to more sophisticated designs (such as Doherty or Envelope Tracking), the cost of the components in the a Class-AB PA is lower. Because there are fewer components in the implementation design, it is simpler and requires less money to produce

and implement.

Complexity: The design Complexity of Class-AB is Low since digital pre-distortion and complex signal conditioning are not needed. Integration: Less effective for wideband 5G signals and needing greater power consumption, but easier to integrate.

Generally Class AB Power Amplifier:-

PAE: Moderate PAE, often in the range of 50-72%. However, their efficiency tends to degrade at high levels of back-off.

Linearity: Class-AB Power Amplifier provides an excellent balance between efficiency and linearity.

Power Output: Power output ranges from moderate to high, making it appropriate for applications with moderate power requirements.

Gain: Typically offers moderate gain levels.

2.1.2 Doherty Power Amplifier Analysis

strength power amplifiers are a very important idea in wireless communication systems because they boost signal strength before transmission. One type of power amplifier that has gained significant attention for massive MIMO applications is the Doherty power amplifier. The Doherty approach is frequently used to build PA for wireless systems and, in particular, in base stations that function in the LSC Band with time-varying envelope transmissions such as WiMax, WLAN, and cellular networks [19]. Using vacuum tubes, W. H. Doherty originally suggested the Doherty PA in 1936. A 50 kW transmitter radio station in Kentucky was the first to employ this novel gadget, which increased the RF power amplifier's efficiency. These days, mobile communication systems that use semiconductor devices at higher frequencies have reinvented the amplifier in response to the introduction of new communication standards [3]. The active load-pull approach, upon which the Doherty amplifier is built, has been extensively described in the literature [3]. The Doherty configuration's use of what is now known as an active load-pull mechanism is one of its intriguing features. Since RF designers typically consider RF loads to be passive lumps of metal and dielectric, the idea that the resistance or reactance of an RF load may be changed by applying current from a second, phase coherent source is somewhat foreign to them [7]. Among the various architectures available for power amplification,

Doherty power amplifiers stand out due to their efficiency and linearity, particularly in broadband applications. By utilizing a combination of two amplifying stages a main and a peak amplifier DPAs can achieve high efficiency across varying output power levels, a feature that is increasingly critical in modern communication systems, especially in 5G massive multiple-input multiple-output applications. Recent advancements have demonstrated that integrating active devices fabricated with gallium nitride (GaN) with passive components from the gallium arsenide (GaAs) process can yield frequency bandwidths of up to 4.4–5.0 GHz while ensuring saturation powers over 45.0 dBm [20]. Moreover, the implementation of digital pre-distortion (DPD) has shown significant improvements in linearity, yielding adjacent channel power ratios better than -40 dBc [20]. This is a major advancement in power amplifier technology and makes DPAs ideal for high performance and efficient applications. One example of the range that becomes available when components are coupled in an unconventional way is the Doherty amplifier. Figure 2.1 provides an illustration of the fundamental idea. For ease of use, the two gadgets will be referred to as Main and Auxiliary. The total power of both devices is the ultimate maximum RF output power. The auxiliary amplifier shuts down and stops producing RF power when the input drive level is decreased. It is assumed that it will also stop drawing DC (either because it is in Class B or because it has external control circuitry) at a specific point, usually 6 dB below the maximum composite power. Therefore, the active device periphery has been decreased by around 50% below the 6 dB back-off limit (assuming the two devices have equal I_{\max} amount, which; at lower power levels, will greatly increase efficiency. With the exception of higher power levels where the entire periphery is needed, half of the device's peripheral is essentially turned off.

When the auxiliary device is operating and the primary device is maintained at a constant maximum voltage, the Doherty amplifier's crucial operation takes place. In order to preserve maximum voltage swing and efficiency, this is accomplished via the load resistance, whose effective value dynamically lowers with increasing drive level due to the load-pulling action of the auxiliary amplifier. In this regime, the output power rises proportionately to the input voltage drive level, resulting in a square root characteristic on a linear power scale. A "three-halves" power transfer characteristic is produced by the auxiliary amplifier, which is subject to an upward load-pull effect and produces an output power proportionate to the cube of the growing input voltage amplitude. As seen in Fig-

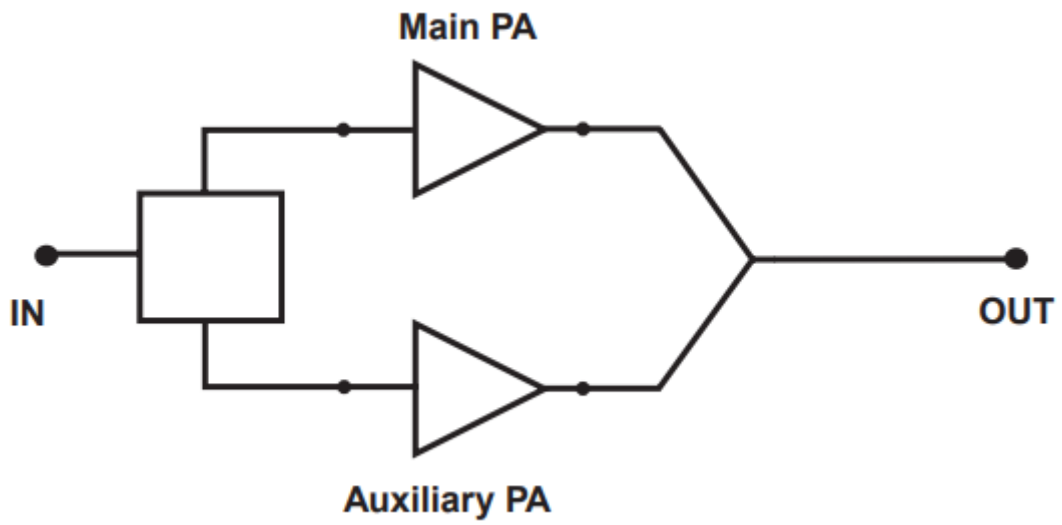


Figure 2.1: Doherty PA, basic configuration.

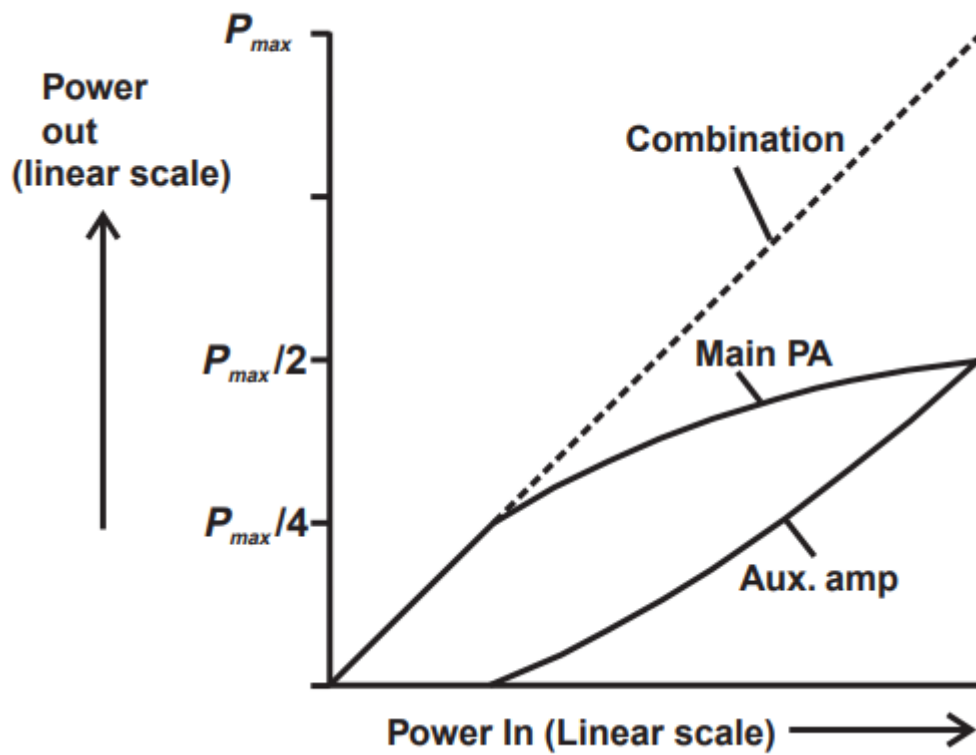


Figure 2.2: power output characteristics of a Doherty PA.

ure 2.2, these two features work together to provide a composite linear power response that maintains near-maximum efficiency all the way down to the 6 dB back-off efficiency point [7].

Because of its great linearity and efficiency, the Doherty power amplifier is a good fit for huge MIMO systems. To achieve high efficiency and linearity, the Doherty power amplifier combines an auxiliary amplifier with a main amplifier. Usually, the auxiliary amplifier is biased in class C while the main amplifier is biased in class AB. This asymmetric arrangement enables increased linearity and efficiency. The Doherty power amplifier (DPA) is gaining popularity among the suggested PA solutions because of its high back-off efficiency and very simple construction [21]. However, the scheme's rather low linearity, particularly in terms of AM/PM Change, necessitates the use of linearization blocks based on predistortion or feedforward [22].

The DPA improves efficiency by splitting the operation of the amplifiers

Energy Efficiency: A well-known design for enhancing power efficiency in wireless communications is the Doherty Power Amplifier (DPA). This architecture is particularly useful in situations when amplifiers must function across a large dynamic range, such as in 5G networks. The DPA improves efficiency by splitting the roles of the amplifiers; only the Main Amplifier is active at low input power levels. When the load impedance is high and the auxiliary amplifier is off, the main amplifier operates more effectively. The Auxiliary Amplifier continues to operate as the input power increases, lowering the load impedance that the Main Amplifier detects. Even at higher power levels, this keeps both amplifiers operating effectively. the total power-added efficiency (PAE) can be described as [23].

$$PAE = \frac{P_{out} - P_{in}}{P_{DC}} \quad (2.1)$$

Where:

- P_{out} describe an Output Power of an amplifiers, P_{in} describe an Input Power of amplifiers

and P_{DC} is the DC Power consumed by the Amplifier

A typical amplifier loses a significant amount of efficiency as the output power drops from its maximum. However, the Doherty design maintains a higher PAE throughout a larger range of output power levels, especially when accounting for the varying load impedance of the amplifiers.

By dynamically altering the load impedance and presenting it to the amplifiers according to the input power level, load modulation enables the Doherty PA to maintain its high efficiency over the whole dynamic range. This can be represented mathematically as:

$$Z_L = Z_{opt} \times \frac{P_{peak}}{P_{current}} \quad (2.2)$$

Where: Z_L symbolizes the load impedance that the primary amplifier perceives, Z_{opt} represents the optimal load impedance at peak power, P_{peak} represents the peak power, and $P_{current}$ represents the current output power.

- **Linearity:** It is appropriate for signals with a high peak-to-average power ratio due to its good linearity at back-off power levels.

Regarding signal processing, if the main amplifier contributes to the linear component of A_1x and the peaking amplifier plays a part in to the nonlinear component A_2x^2 , and the sum of the output may be written as:

$$y(t) = A_1x(t) + A_2x^2(t) \quad (2.3)$$

The DPA reduces the second-order distortion factor $A_2x^2(t)$ by carefully selecting when to activate the peaking amplifier. This keeps the overall output $y(t)$ near a linear function of the input $x(t)$.

- **Power Output:** Can deliver high power output, especially at peak efficiency points.

The total output power P_{out} of the Doherty amplifier is the sum of the output power contributions from the Main Amplifier $P_{out, main}$ and the Auxiliary Amplifier $P_{out, aux}$

$$P_{out} = P_{out, main} + P_{out, aux} \quad (2.4)$$

- **Gain:** Provides minor gains, although PAE is the more important element.

The gain G of a Doherty amplifier can be expressed as the ratio of the whole power output P_{out} to the power input P_{in} [23].

$$Gain = \frac{P_{\text{output}}}{P_{\text{input}}} \quad (2.5)$$

Compared to conventional amplifiers, the Doherty amplifier maintains a greater overall gain across a broader range of input powers because it employs two amplifiers that operate in distinct power zones. Only the main amplifier operates at minimum input power levels, and because it is dealing with a large load impedance, the gain is rather high. As input power increases, the auxiliary amplifier helps to maintain the gain by turning on at higher input power levels.

Both amplifiers function more effectively and retain their gain even when the input power fluctuates thanks to the load modulation. This fits the description of:

$$G = G_{\text{main}} + G_{\text{aux}}, \quad \text{where } G_{\text{main}} \propto \frac{1}{Z_{L1}}, \quad \text{and } G_{\text{aux}} \propto \frac{1}{Z_{L2}}. \quad (2.6)$$

By dynamically adjusting the load impedance, the main and auxiliary amplifiers may both increase the gain across a wider range of input power levels.

Cost: Because the Doherty PA has more components than Class AB, including a peaking amplifier, its component costs are higher. and the cost of implementation is moderate because of the intricate design and requirement for additional circuitry, such the load modulation network.

Design complexity : is higher than in Class AB, necessitating more complicated design methods for appropriate load modulation and its integration. maintains linearity while more complex DPD and control methods are needed. This leads to notable efficiency gains, particularly for high-bandwidth signals.

2.1.3 Envelope Tracking Power Amplifier

Envelope tracking is the process of altering the RF PA's supply voltage in accordance with the modulated waveform's envelope. Due to its ability to increase power amplifier

efficiency and linearity, envelope-tracking power amplifier technology is becoming more and more popular in the field of radio frequency communication systems. This technology uses a dynamic voltage supply to achieve a balance between linearity and efficiency, which is challenging for traditional constant voltage power amplifiers. Envelope-tracking power amplifiers meet strict linearity requirements while achieving high efficiency across a broad dynamic range and bandwidth by following the envelope of the input signal and dynamically modifying the output load. By directly coupling supply voltage modulation to the radio frequency (RF) output, ET amplifiers maintain exceptional linearity while improving power-added efficiency (PAE) significantly, often exceeding 70% in optimal conditions, as evidenced in various studies [24]. Research has shown that envelope-tracking power amplifiers offer significant efficiency improvements compared to fixed bias supply and conventional envelope-tracking systems. This improvement in efficiency makes envelope-tracking power amplifiers a promising technique for enhancing the performance of radio frequency communication systems, including applications in 5G base stations. Furthermore, although envelope-tracking power amplifiers can handle signals with a larger bandwidth, the overall linearity may be compromised. The linearity problems with envelope-tracking power amplifiers can be lessened by using digital distortions and load modulation. By altering the impedance observed at the transistor's drain, load modulation architectures, such as dynamic and active load modulation approaches, can be used for envelope-tracking power amplifiers to attain high efficiency [25].

The rise of 5G networks requires power amplifiers that can efficiently handle the higher data rates and expanded bandwidths [25]. Envelope Tracking Power Amplifiers are becoming a favorable option in power amplification for 5G networks. By adjusting the voltage supplied according to the signal envelope using envelope-tracking technology, they help to improve overall efficiency. There is a wealth of scholarly articles that have explored the creation and utilization of these power amplifiers across different uses such as LTE and WLAN systems, showcasing their versatility and potential applications. For example, a research paper [26]; explains the development and deployment of an envelope-tracking power amplifier with a broad channel bandwidth of up to 30 MHz that is especially suited for LTE applications. The significance of a supply modulator with precise and quick envelope monitoring for wideband operation is emphasized in the article. A high-efficiency wideband envelope tracking power amplifier for 4G applica-

tions is presented in another study [25]. the amplifier consists of a GaAs Transistor RF power Amplifiers stage and a CMOS envelope-amplifier. Its average LTE output power is 27.6 dBm, and its gain is 26.5 dB, resulting in a total PAE of over 46%. Another article examines the application of baseband pre-distortion to enhance linearity in WLAN 802.11g systems using envelope-tracking power amplifiers. For an OFDM power output of 20 dBm at 2.4GHz, the system uses a GaAs MESFET class-AB Radio frequency PA and a high-efficiency wide-bandwidth envelope amplifier to achieve an overall system drain efficiency of 30%. these illustrations show the versatility and efficiency of envelope-tracking power amplifiers in 5G network applications [9]. All things considered, envelope-tracking power amplifiers present a viable way to meet 5G networks' power amplification requirements. They provide high efficiency and wide bandwidth operation, making them suitable for the demanding data rates and expanded bandwidths of 5G networks [26].

A major factor in raising 5G networks' capacity and performance is huge MIMO technology. It allows for increased network capacity by utilizing multiple antennas to simultaneously transmit and receive data, resulting in improved spectral efficiency. Furthermore, envelope-tracking power amplifiers can complement massive MIMO systems in 5G networks by providing efficient and linear amplification of the transmitted signals when compared to Class AB and Doherty Power Amplifiers. As a result, adding envelope-tracking power amplifiers to large MIMO systems can improve the 5G network's overall performance and efficiency, which will eventually improve user experience and make it possible to send high-quality, fast data. Envelope-tracking power amplifiers are especially beneficial for 5G networks when used in LTE applications with extensive channel bandwidths of up to 30 MHz. Their ability to operate across a wide frequency range makes them well-matched for the demands of LTE applications, enabling high efficiency and linearity [25].

Envelope tracking power amplifiers are a promising solution for 5G networks because of their high efficiency, wide bandwidth operation, and capability to handle large transmit power levels. Their incorporation into massive MIMO systems can further enhance the capacity and performance of 5G networks. To sum up, envelope-tracking power amplifiers present a viable way to meet 5G network power amplification requirements. Their high efficiency, wide bandwidth operation, and capability to handle large transmit

power levels make them well-suited for the demanding data rates and expanded bandwidths of 5G networks. Additionally, the integration of envelope-tracking power amplifiers into massive MIMO systems can further enhance the overall performance and efficiency of 5G networks. By providing efficient and linear amplification of transmitted signals, envelope-tracking power amplifiers can significantly contribute to improving spectral efficiency and user experience in 5G networks. Overall, the use of envelope-tracking power amplifiers in 5G networks, particularly in LTE applications with extensive channel bandwidths, showcases their potential to drive advancements in the telecommunications industry. In summary, envelope-tracking power amplifiers offer a solution for improving both spectral efficiency and overall performance in 5G networks. How Envelope Tracking Improves the Efficiency and Linearity of the 5G network will be discussed as follows.

Energy Efficiency Depending on the input signal's amplitude, envelope tracking dynamically modifies the voltage supply. By modulating the supply voltage $V_{DD}(t)$ to follow the envelope of the input signal $V_{env}(t)$, the amplifier is guaranteed to function at a higher voltage during peaks and a lower voltage during low signal amplitude periods.

Mathematically, the supply voltage is expressed as:

$$V_{DD}(t) = V_{env}(t) \quad (2.7)$$

With this change, the amplifier operates closer to its maximum efficiency point and dissipates less power. ET greatly increases PAE by making sure that the power supply is precisely matched to the output signal needs, especially in situations where there is a power outage.

The PAE with envelope tracking can be written as:

$$PAE_{ET} = \frac{P_{out} - P_{in}}{V_{DD}(t) \cdot I_{DD}(t)} \quad (2.8)$$

Where: - $I_{DD}(t)$ is the current drawn by the amplifier at any given time, - $V_{DD}(t)$ is dynamically adjusted according to the signal envelope.

By reducing $V_{DD}(t)$ when P_{out} is low, ET minimizes power consumption and improves overall efficiency.

Envelope Tracking Linearity

By keeping a suitable supply voltage $V_{DD}(t)$ that tracks the signal envelope, envelope tracking improves linearity. This allows the amplifier to operate closer to its linear area even when the input signal's amplitude fluctuates.

This effect may be mathematically seen by looking at the gain of the amplifier:

$$y(t) = A \cdot x(t) + D \cdot x(t)^2 \quad (2.9)$$

Where: $y(t)$ describes the output signal, A describes linear gain coefficient, $D \cdot x(t)^2$ represents the non-linear distortion terms.

By dynamically adjusting $V_{DD}(t)$ in line with the envelope $V_{env}(t)$, ET minimizes the non-linear distortion terms $D \cdot x(t)^2$, decreasing intermodulation distortion as a result. This is due to the amplifier's avoidance of saturation and compression, which at higher input power levels usually result in nonlinearities.

The improved linearity can be seen in the reduction of higher-order distortion components, such as:

$$IMD \propto \left(\frac{V_{DD} - V_{peak}}{V_{peak}} \right)^2 \quad (2.10)$$

Where V_{peak} is the peak signal voltage. ET reduces the deviation of V_{DD} from the optimal value, thus reducing distortion.

Envelope Tracking Improves Output Power

Since Envelope Tracking dynamically adjusts the supply voltage $V_{DD}(t)$ to match the envelope of the input signal, the amplifier can operate at higher supply voltages during periods of high input signal amplitude, enabling it to achieve higher output power without saturation or clipping.

Mathematically, the output power P_{out} is related to the supply voltage by:

$$P_{out} = \frac{V_{DD}^2}{2 \cdot Z_L} \quad (2.11)$$

Where: the symbol V_{DD} represents the voltage supplied to the amplifier, and Z_L is to represent the load impedance.

Because the supply voltage of ET amplifiers is not set and instead follows the signal envelope, it may optimize output power as needed. This dynamic change increases the amplifier's overall output power capacity, especially for signals with high PAPR.

The instantaneous power during high-amplitude portions of the signal is higher in ET amplifiers because $V_{DD}(t)$ increases in response to the signal, allowing the amplifier to reach higher peak output power.

The instantaneous power during high-amplitude portions of the signal is higher in ET amplifiers because $V_{DD}(t)$ increases in response to the signal, allowing the amplifier to reach higher peak output power.

Envelope Tracking Improved Gain

By guaranteeing that the supply voltage $V_{DD}(t)$ is consistently suitably matched to the envelope of the input signal, envelope tracking preserves better gain throughout a broad range of input power levels. For a wider range of signal amplitudes, this enables the amplifier to function at its peak efficiency point.

The amplifier's gain G may be expressed mathematically as follows:

$$G = \frac{P_{out}}{P_{in}} \quad (2.12)$$

Since $P_{out} \propto V_{DD}^2$ and $V_{DD}(t)$ tracks the signal envelope, Even with large variations in the input power, the amplifier may maintain a more consistent output power and, thus, a more consistent gain.

The gain with envelope tracking can be expressed as:

$$G_{ET} = \frac{V_{DD}^2(t)}{P_{in}} \cdot \frac{1}{Z_L} \quad (2.13)$$

Where $V_{DD}(t)$ dynamically modifies to track the input signal's envelope, keeping a greater gain even when the input power is reduced.

Cost: The components of the ET PA are more expensive than those of Class AB and Doherty because an additional envelope modulator and dynamic power supply are needed,

& how it's put into practice Increased total cost as a result of the intricate design and sophisticated control circuits needed to track the signal envelope in real-time.

Complexity: Because of the dynamic nature of envelope modulation and the requirement for exact signal and power supply synchronization, design complexity is quite high. Integration is difficult since the power supply, control electronics, and PA must be tightly integrated. For ET PAs to be linear and efficient, advanced digital signal processing is usually needed.

2.2 Massive MIMO

In the field of wireless communications, massive MIMO technology has drawn a lot of interest because of its revolutionary potential to drastically change the way that data is sent and received. The foundation of massive MIMO systems is the employment of several antennas at the base stations, potentially hundreds or even thousands. Many antenna elements are used in massive MIMO systems, and each one usually has its own Power Amplifiers. Among the main advantages of the massive MIMO approach are enhanced spectral efficiency, greater energy economy, and the ability to service several clients concurrently. For huge MIMO to be successful, the power amplifier is one of the most crucial elements. Due to the large antenna scaling, only a small portion of the overall transmit power is needed for each antenna, making low-cost, low-power amplifiers possible. This is a big benefit over conventional MIMO systems, which require the power amplifiers to run at greater power levels, which adds complexity and expense. In traditional base stations, the power amplifier in radio front ends is a major source of power consumption. The nonlinear behavior of a PA causes Inband and Out-of-Band distortion. Error vector magnitude and adjacent channel leakage ratio criteria are defined by 3GPP in order to prevent this [27]. Digital pre-distortion is a useful technique for boosting PA efficiency and lessening the impact of non-linearities. However, after the introduction of new communication technologies such as massive MIMO [28]. Checking to see if the same needs and solutions still apply is crucial. DPD implementation in a large antenna regime is shown to cause serious power, bandwidth, and scalability issues, according to current studies [29]. Through spatial multiplexing, digital beamforming is employed in massive MIMO (mMIMO) to achieve high data rates and spectrum efficiency [30] [31]. Because

of the large array gain and the several antennas on each transmit chain, the base station's total transmit power may be decreased. Thus, it is expected that the power requirements per component would alter in 5G systems that employ Massive MIMO.

Massive MIMO has a big influence on power amplifier design and overall system concepts. It is a vital technology for 5G and beyond. Massive MIMO provides great spatial resolution by utilizing hundreds of antennas, which makes low-power, low-cost PAs possible [32]. The shift from costly, highly linear PAs to a variety of smaller, more straightforward amplifiers is what caused the change in base station cost and power usage. Although the standards for individual PA linearity have been loosened, the cumulative impact of several antennas still calls for careful consideration of efficiency and distortion [33]. Large-scale antenna arrays also provide difficulties with hardware complexity, channel prediction, and energy consumption in other system components, necessitating creative solutions for real-world use [34]. Massive MIMO, therefore, represents a paradigm change that necessitates a comprehensive system-level strategy that strikes a balance between hardware complexity, PA design, and overall system performance. The main challenge with massive MIMO is the massive number of PAs required for the DPD algorithm to track and linearize the behavioral changes of each PA. The hundreds of PAs in a large MIMO transmitter cannot be fully linearized with a single DPD. Furthermore, giving each PA a unique DPD throughout the duration of the linearization is challenging and ineffective. So for this Massive MIMO problem, paper [35] uses the suggested low-complexity DPD technique to overcome these issues. This might significantly raise the processing and power needs, depending on the scale of the system. Understanding how PAs are constructed and integrated into Massive MIMO systems is essential for optimizing performance, ensuring signal integrity, and maintaining energy economy in complex wireless communication networks. In the Next chapter, we will discuss in detail How PAs Integrated to Massive MIMO and Improve Efficiency and Linearity of Wireless Communication. also The Role of Digital Pre Distortion Techniques in Improve PA Performance.

Chapter 3

Power Amplification in 5G Network

Radio Frequency Power Amplifier amplifies a signal that is poorly modulated. In fact, 10% of the world's power generation is thought to come from mobile communication combined [36]. Thus, preserving a high level of power efficiency in 5G networks is essential to their long-term growth. In wireless communication networks, power amplifiers are essential, especially for 5G Massive MIMO applications. Since PAs are the component in the front end that uses the most power, their effectiveness affects how much power the entire 5G network uses [37]. The need for faster data speeds, more capacity, and more efficient networks is growing as 5G technology develops. Delivering high-quality signals at high enough power levels to guarantee dependable network connectivity requires power amplification. Because 5G applications demand higher frequency bands and larger bandwidth, power amplifiers must overcome special hurdles. These challenges include the requirement for amplification techniques with excellent linearity and high power efficiency to ensure minimal power loss and signal distortion. A power amplifier's power efficiency has a direct bearing on the network's energy usage, making it a crucial design factor for 5G systems. Moreover, 5G networks commonly employ Massive MIMO technology, which uses many antennas at the transmitter and receiver ends. Massive MIMO improves spectrum efficiency and overall system performance by utilizing multiplexing gains and spatial diversity. Massive MIMO systems' power amplifiers must be able to handle the demands of high-capacity data transmission while also providing outstanding quality of service and dependability. To overcome these issues, power amplifier technologies need to be thoroughly examined and adjusted for their effi-

ciency, linearity, power consumption, cost, and implementation complexity. It is essential to assess various power amplifier types while keeping in mind the particular requirements and constraints of these systems in order to identify the optimal options for 5G networks. There will be some ideas on the Efficiency vs. Linearity Trade-off in Power Amplifiers for 5G Massive MIMO Applications by understanding the Linearity of Power Amplifiers for 5G Networks and the Efficiency of Power Amplifiers in 5G Networks.

3.1 Linearity of Power Amplifiers for 5G Networks

Linearity is a crucial feature for amplifiers in general, and power amplifiers in particular since they have to withstand huge signal excursions, which invariably lead to distortion and a compromise in signal purity. The linearity of the amplifier determines how well the input signal is reproduced at the output; a linear amplifier is defined by an output that varies proportionately to the input, i.e., in terms of a good gain and in terms of phase response. Power amplifiers are non-linear systems by nature [37]. An equation that is polynomial can be used to describe them. The majority of PA linearization methods provide the proper adjustments by comparing the output to the amplitude and phase of the input RF envelope. The primary difference between the two most significant linearization approaches now in use is the way the correction is implemented [7]. Since power amplifiers are non-linear systems by nature a polynomial expression that can be used to describe and characterize them mathematically as equation 3.1 [37].

$$y(t) = \alpha x(t) + \beta x(t)^2 + \gamma x(t)^3 + \dots + \kappa x^n \quad (3.1)$$

Memory effects are not taken into consideration by this formula, which is a simplified model. Inside the linear zone, the nonlinear components barely make a difference in relation to the coefficient of $x(t)$ which is represented as (α) . When the amplifier achieves compression and the input-output proportionality disappears, they become much more important. The released signal is corrupted and might not function [7]. unwanted duplicates of the output signal at various frequencies are produced when these increased powers of x are present in a multi-tone excitation, such as an LTE-modulated signal. We identify the second and third order distortion products at harmonic frequencies. These

can be sorted out and are often far enough. Conversely, Inter Modulation Products produce replicas of the original signal that are extremely near to the actual signal band by appearing at combinations of the various signal frequencies [37]. In addition to the inherent nonlinearity of the device, memory effects deteriorate the signal that is released. Because the output value of dynamic signals depends on both the input or output state that is currently occurring and the previous input or output state, they display this non-static behavior. Both short-term (a few microseconds) and long-term (milliseconds to indefinite) memory effects are possible [38].

The main origins of memory distortion are:

- Effects of frequency memory: Transistors and matching networks, for example, do not react consistently across all frequencies when working with wideband signals, which have a wide range of frequencies. The effect is Distortion results from differences in phase response and gain for various frequency components. Intermodulation products, which lower the signal quality, might be the result of non-linear interactions between various frequencies. Given the prevalence of wideband transmissions in high-speed communication systems like 5G, the significance of frequency memory effects is especially crucial.
- Bias memory effects: The bias voltage (DC operating point) fluctuates as a result of dynamic changes in the input signal envelope. There is a delay between changes in voltage or current if the bias line displays inductive properties. The Effects of One is the biased memory effect, which causes the signal to become non-linear and distorted due to the lag. Another is Performance is impacted by envelope modulation, which results in an imbalance in the current-voltage behavior. As an illustration, These effects show themselves in power amplifiers as spectrum regrowth or amplitude modulation to phase modulation conversion.
- Temperature effects: As the device runs, the heat created by the current flow and power dissipation impacts the device characteristics like mobility, threshold voltage, and resistance. The Impact of This Temperature Effect is one; Thermal fluctuations produce changes in gain and phase, especially under variable signal circumstances. another is These effects are gradual but can remain as long-term memory distortion.

For high-power devices and systems that need to operate consistently over time, temperature effects are relevant.

- **Technology-related effects:** In Gallium Nitride (GaN) and other semiconductor technologies, charge trapping occurs in defect sites within the material or at interfaces. These traps hold charges temporarily, releasing them over time. Because the device response is dependent on the trapped charge state, the impact is more noticeable in high-frequency and high-power applications. For instance, charge trapping can result in instability and decreased efficiency in GaN-based power amplifiers. This has very long-term memory effects.
- **Device degradation:** Stress from high voltages, currents, and temperatures causes the device's physical properties to deteriorate over time. Mechanisms such as electromigration, hot carrier injection, and material fatigue contribute to this degradation, which has two main effects: first, it changes the electrical behavior of the device, leading to long-term changes in gain, phase, and efficiency; second, it introduces persistent memory effects that build up with use; and third, reliability in long-term operations, like base stations or satellite communications, is critically affected by device degradation.

Additionally, understanding the concepts of Amplitude Modulation to Amplitude modulation, AMPM, error vector magnitude, and adjacent channel power ratio is crucial when discussing linearity in 5G networks.

Amplitude Modulation to Amplitude modulation: The measurement of the difference between the amplitude of the input signal and the signal amplification is known as amplitude modulation to amplitude modulation. As a function of input or output power in dBm, it is frequently expressed as dB. At minimum input signal levels, amplification is typically linear and the output amplitude follows the input signal amplitude with constant gain, while large input signals cause the gain to compress. The linearity of an amplifier, or the range of input and output signal levels it can manage, is shown by AMAM [39].

AMPM: Amplitude modulation to phase modulation, or AMPM, is a measurement of how the output phase changes in response to the input signal's amplitude. It is frequently stated as a function of input or output power in dBm and expressed in degrees. The

output phase follows the input signal phase with a constant phase shift when the amplification is linear for low input signal levels. However, the PA begins to depart from linear amplification as the input signal's amplitude grows, and the output phase may lead or lag in relation to the phase for low signal levels. For different output signal levels, or for which input and output signal levels an amplifier may be utilized, AM-PM indicates how effectively the amplifier maintains the phase information.

Additionally, it's important to review the methods used to assess and characterize the linearity of power amplifiers used in 5G networks while talking about their linearity. A PA's nonlinear nature can result in two different kinds of distortion: inband and out-of-band. 3GPP defines standards for neighboring channel leakage ratio and error vector magnitude to limit this [27]

Error Vector Magnitude: EVM is the constellation diagram's rms deviation from the intended points divided by the RMS amplitude of the desired point. In actual use, the Error-Vector Magnitude and the Adjacent Channel Leakage Ratio are two often used metrics to describe an amplifier's linearity.

$$ACLR = 10 \log_{10} \frac{P_{\text{out, adj}}}{P_{\text{out, ref}}} \quad (3.2)$$

EVM characterizes the in-band distortion and, consequently, In this section, the power in the reference (primary) channel ($P_{\text{out, ref}}$) is divided by the power in the adjacent channel ($P_{\text{out, adj}}$).

ACLR neighboring channel leakage ratio is the power in one of the neighboring channels divided by the transmitted power in the main channel. The ACLR, a commonly used linearity evaluation, is the focus of PA designer's practical measurements. $P_{\text{out, adj}}$ and $P_{\text{out, ref}}$ represent the power in both the emission channel and the neighboring channel. We can measure both right and left ACLR in the neighboring and next (alternative) channels. ACLR describes out-of-band emissions. Over the years, numerous methods have been put forth and proven to be effective in reducing amplifier non-linearities. Reducing the power amplifier's average power is the easiest method to implement. At very low efficiency, the output signal remains in the small-signal, linear area. The feedback loop method of linearization is the most basic. To remove the distortions, an error signal is sent from the output to the power amplifier's input. Unfortunately, this strategy may

be highly damaging in high-frequency circuits since it can induce instability, especially with larger bandwidth signals [40]. The outcomes of this research study are likely to have far-reaching ramifications for network operators, researchers, and industry stakeholders. This research can help to produce more sustainable and dependable wireless communication systems that meet the ever-increasing needs of the digital era by developing techniques and recommendations for establishing energy-efficient and high-performance 5G mobile broadband networks.

3.2 Efficiency Enhancement of Power Amplifiers for 5G Networks

The two main design criteria for 5G are strong data transfer speeds in gigabits and low power consumption systems. As a result, we must investigate the efficiency of the Power Amplifier employed in Massive MIMO [7]. There are two fundamental issues with power amplification of amplitude-modulated RF transmissions. The first is that if the power amplifying device is utilized at its full RF power level, the envelope, and hence the modulating signal, will be slightly warped. The second is that traditional power amplifier designs only achieve optimal efficiency at a single power level, which varies depending on the circuit design but is often close to the device's maximum rated power. As the drive power is reduced from this point, efficiency declines dramatically and heat dissipation increases, despite the fact that RF output power decreases. The total result is to measure a mean efficiency that is substantially lower than the efficiency at the highest power or PEP, level [7]. It is more challenging to tackle the first problem, which only calls for making the amplifier's transfer characteristic more linear within a specific power range, and the solutions are always constrained. Particularly higher linearity will always have a price, including baseband frequency limitations and, most significantly, decreased efficiency. However, in many transmitter applications, such methods are required and commonly used. The latter form is the only one that the word "linearization" should logically relate to. Some implementations will inevitably combine linearization and efficiency improvement strategies, while on the other hand, some particular strategies can be used with either linearization or efficiency enhancement as the main objective [7].

under our study, we examine the three power amplifiers' efficiency, paying particular attention to methods that increase efficiency under modulated signal envelope situations without explicitly enhancing linearity. The Linearity of Power Amplifiers for 5G Networks Section goes into further detail on linearization strategies. This category includes the Doherty Power Amplifier and the ET Power Amplifier, two traditional methods.

3.3 The Role of Digital Pre Distortion Techniques in Improve PA Performance

One of the most crucial elements of communication systems for extending battery life and lowering system expenses is PA efficiency. PAs often consume the most amount of power in communication systems. Increases in PA efficiency have the potential to significantly lower cooling and power needs. One effective method to lessen the impact of nonlinearities and increase PA efficiency is digital pre-distortion (DPD).

In communication systems, power amplification is crucial because it boosts signal intensity and ensures reliable transmission [41]. The amplification process, however, may cause non-linear distortions in the signal, resulting in adjacent channel interference and decreased system efficiency [9]. Researchers have been looking at ACLR optimization and digital pre-distortion methods to overcome these issues. In order to provide better communication quality, these techniques aim to linearize the power amplifier's response, increasing its efficiency and lowering signal distortions [42]. By using digital pre-distortion techniques, the distorted signal can be corrected in advance to mitigate non-linear distortions caused by the power amplifier [9]. Using this method entails examining the power amplifier's nonlinear behavior and creating a digital pre-distortion algorithm that compensates for these distortions. This method allows the signal to be pre-compensated before it reaches the power amplifier, which improves system performance and yields a more linear output. The power transistor operating class and the input or output back-off selected to run the PA determine the efficiency of the PA. There are trade-offs between linearity and efficiency for different PA classes. For example, a Class-AB design sacrifices some linearity to boost efficiency, whereas a Class A amplifier has the highest linearity but the lowest efficiency. But these days, base stations employ Do-

herty amplifiers. A Doherty PA is a cross between Class AB and Class C. It provides better linearity and greater efficiency than other PA classes. To achieve the strict linearity standards of 5G signals, Doherty Linearity—which is reasonable linearity—often necessitates digital pre-distortion. Thus, in regard to our task, We use the Doherty power amplifier to examine the impact of DPD on the power amplifier in order to assess the general characterization of power amplifiers in communication systems. The simulation's outcome may be seen in the next chapter.

Several obstacles stand in the way of DPD deployment in contemporary 5G networks; including broad bandwidth. In order to achieve significantly faster upload and download speeds than previous generations, 5G systems need to be able to accept greater bandwidth signals. The instantaneous bandwidth (IBW) of a 5G system can reach 400 MHz. The higher signal bandwidth presents two challenges for DPD. First of all, wideband signals cause PAs to show greater memory effects, which are harder to define and adjust for using more sophisticated modeling approaches. Secondly; To extract an appropriate DPD model, it is necessary to enhance the feedback channel in the adaptation chain of the DPD model. The feedback route sampling rate must typically be high enough for DPD adaptation to capture five times the signal bandwidth, which means that as bandwidth grows, implementation complexity and expense will also increase.

DPD is one of the main building blocks of the digital front end of a communication system. It increases the power efficiency of the system by linearizing the PA. The PA must operate with a large back-off in order to meet the spectrum emission mask without DPD, which reduces output power and overall power efficiency. To supply the desired output power, a PA with a much higher specification is needed. This significantly raises the cost of the system. DPD provides a cost-effective solution for achieving the required output power while adhering to spectrum emission standards.

Chapter 4

Simulation results and discussion

Based on different interpolated output power levels, this chapter covers the performance study of the Class AB, Doherty, and Envelope Tracking power amplifiers. Key performance metrics including linearity over a variety of output powers, PAE, and gain are the main focus. ADS Software simulations were used to get the results, which shed light on how the amplifier behaved at various power levels. Additionally, MATLAB simulation is used to observe the DPD outcome in order to compensate for nonlinear features in power amplifiers.

4.1 Class-AB Power Amplifier result

A variety of output power levels were used to emulate the Class-AB amplifier. Class-AB has been assigned an output power of 30.00 dBm and 32.00 dBm. Figure 4.1 shows how well the Class-AB power amplifier performed at output power value levels of 30 dBm. by setting the output power to the constant value of 30 dBm; The data reveal significant variations in PAE, interpolated gain, and interpolated gain compression. simulation result From Figure 4.1 shows that at a 1 GHZ; power Gain is 17.16, PAE is 52.76%, and Power delivered is 30 dBm. and this value will Decrease (Figure 4.2) when we operate at a frequency of 850 MHz. at this frequency, the PAE is 51.090%, the gain is 13.700 and the Output power is 30.500 dBm.

Figure 4.3 displays the results for the linearity property of the Class AB PA. It shows

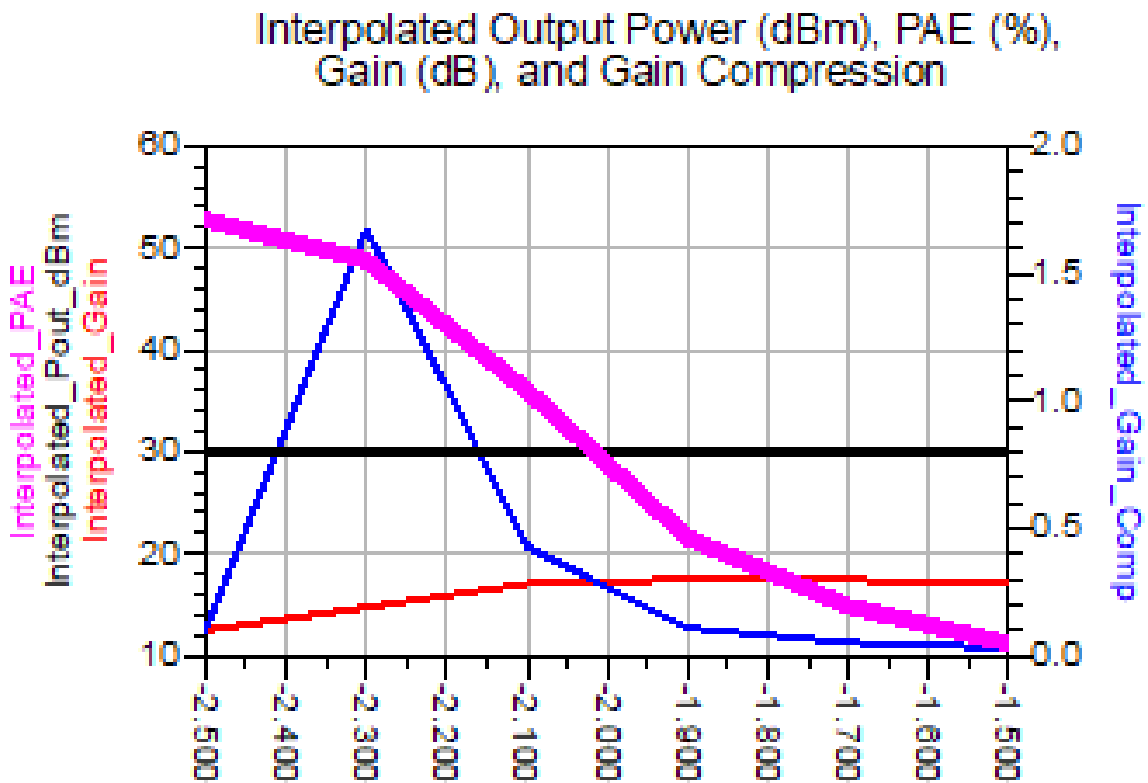


Figure 4.1: Class-AB PA AT 1GHz

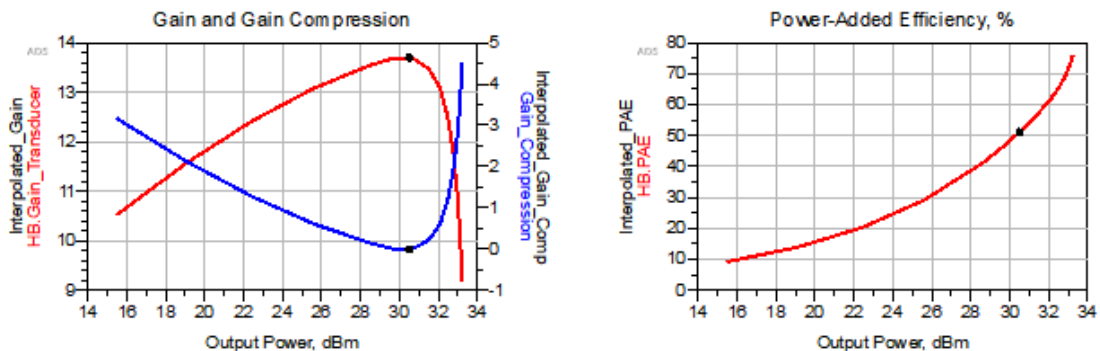


Figure 4.2: Class AB PA Value at 30.500 dBm output power

the relationship between Fundamental Output Power and RF Input Power as well as the features of the Class AB Power Amplifier, including Amplitude Modulation to Amplitude Modulation and Amplitude Modulation to Phase Modulation. The Graph shows positive values for AM-to-AM conversion, indicating that the amplitude modulation increases

predictably with increased source power. AMAM distortion is present when the AM-AM curve deviates from a straight line. At lower input powers, it exhibits a rather steep slope, signifying a strong gain, and then progressively flattens out as the input power rises. As seen by the AM-to-PM values, which fluctuate but stay within a controllable range, phase modulation is also predictable. Because the PA's characteristics (such its capacitance and inductance) change in response to changes in the input power, the output phase fluctuates.

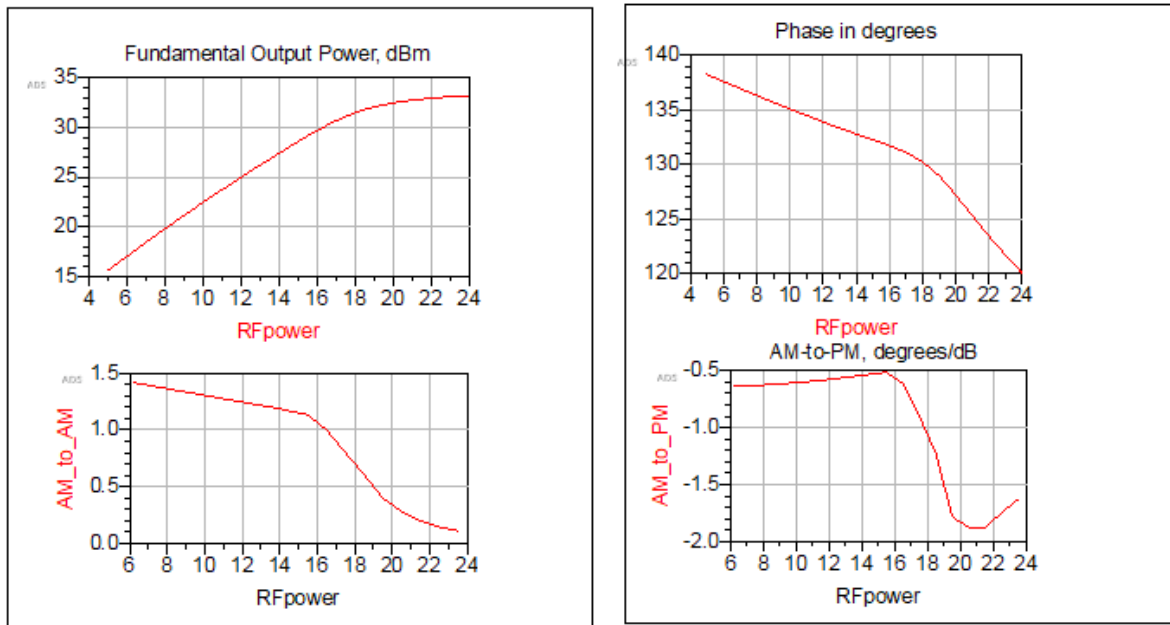


Figure 4.3: linearity property of Class AB PA at 30.500dBm output power

4.2 Doherty Power Amplifier Results

This section displays the Doherty Power Amplifier performance evaluation at various times, including 1 dB compression, at the load that produces the highest Power-Added Efficiency. The Doherty PA was examined for important characteristics including PAE, gain, and supplied power under these circumstances. The Doherty PA is well-suited for high-efficiency operating at back-off power levels.

As we observe from Fig 4.4; displays the load-pull analysis results. the operating point for a power amplifier where the Power-Added Efficiency is at its highest, the Doherty power amplifier achieved a PAE of 71.982%, with a delivered power of 36.543 dBm and

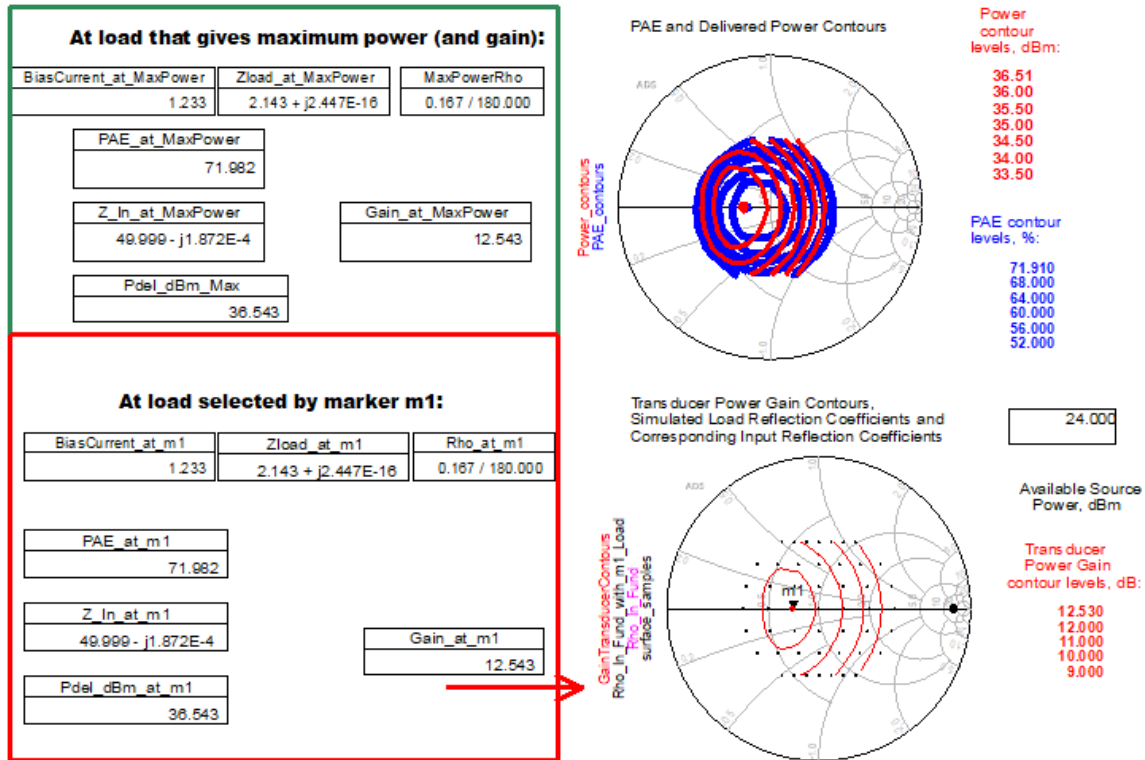


Figure 4.4: Doherty PA at Load That Gives Maximum PAE and Gain

a gain of 12.543 dB. This load condition represents the optimal operational point for maximizing the efficiency of the Doherty PA.

The output power of the DPA's at 34.500 dBm is seen in Figure 4.5. for 1GHz frequency. From the result, we can observe that PAE is 57.318%, and the Transducer power Gain is 9.977.

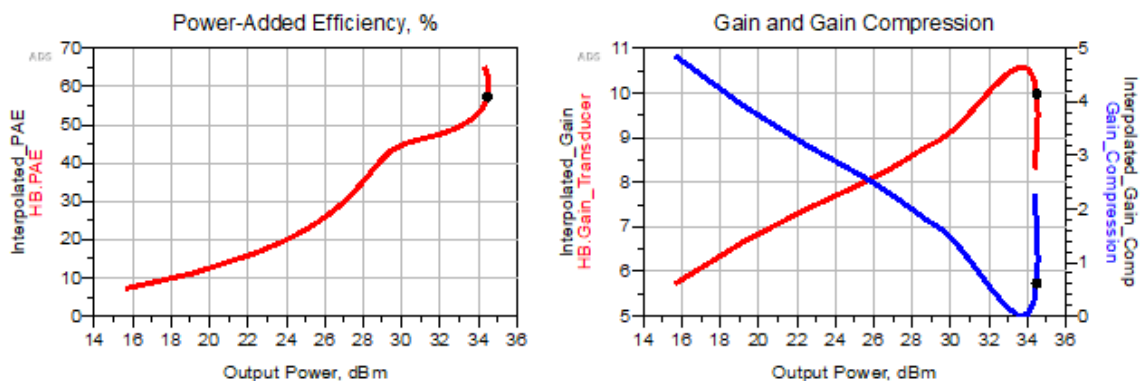


Figure 4.5: Doherty PA At 34.500 dBm output power and 1GHz frequency

the Doherty power Amplifier At 34.000 dBm of 8500 MHZ is Shown in Figure 4.6;

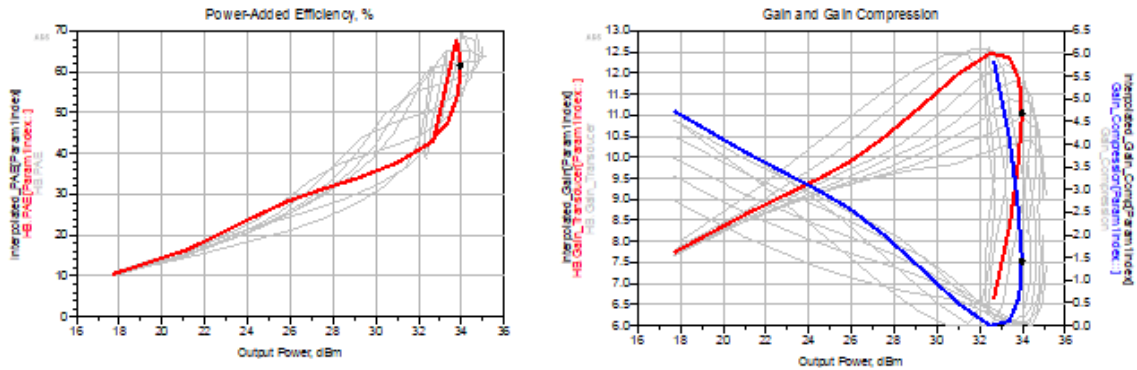


Figure 4.6: Doherty Power Amplifier at 34 dBm output power

from the displayed result we observe that PAE is 65.11 at 34.000 dBm output power, Transducer power Gain is 10.968.

Figure 4.7 shows the linearity property of DPA based on an evaluation of its AMAM and AMPM at its 34.500 dBm power delivered. Fundamental Output Power vs. RF Input Power: The amplifiers' power output curve likewise reaches saturation, albeit it does so at a little higher input power (26 dBm). Smoother transitions in the curve indicate better linearity in the mid-power range. In contrast to the Class-AB PA, the Doherty Power amplifier has a slightly larger linear range before saturation, indicating superior linearization.

Phase vs. RF Input Power: The phase curve shows fewer sharp oscillations at lower power levels and a non-linear hump at higher power levels (22–26 dBm). Despite the hump, the overall phase fluctuation is less severe than with the Class-AB PA. The Doherty amplifier is different from Class-AB in that it has greater phase linearity in the minimum-to-middle power range, despite the fact that it adds nonlinearities near saturation.

The Doherty Power amplifier performs noticeably better than the Class AB PA in terms of linearity in both AMAM and AMPM, particularly in the low-to-mid power range. The linearity of Doherty PA at high frequencies in terms of ACLR and EVM is also shown in the next section.

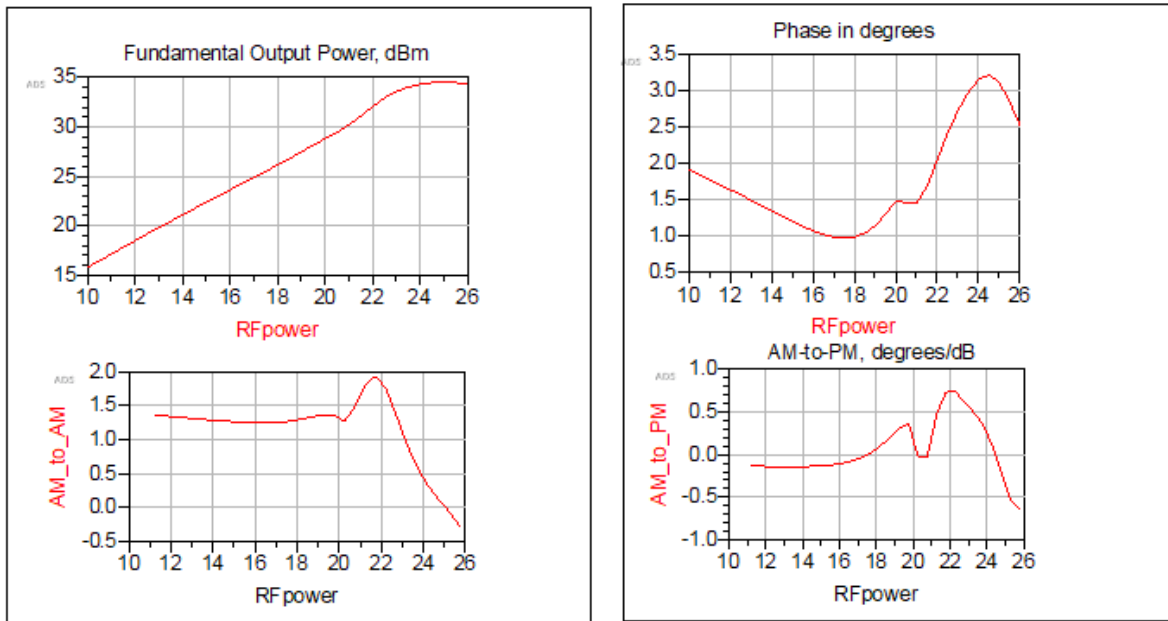


Figure 4.7: AMAM and AMPM properties of Doherty Power amplifier at 1GHz Frequency

4.3 Envelope-Tracking Power Amplifier Result

The simulation of Fig. 4.8 for ET PA demonstrates that the power amplifier performs at fixed bias and without envelope tracking. The findings demonstrate the necessity of envelope tracking with a relatively low mean PAE. PAE mean at this stage is 11.306 dBm. Additionally, the distortion curves for AM-to-AM and AM-to-PM are rather "fuzzy." This is a result of the amplifier's mild memory effects.

After envelope Tracking is applied to the amplifier, see Figure 4.9; the PAE shows improvements. In the design, the source's gain has been changed such that the average power given to the load is roughly the same in both scenarios. From Figure 4.9, the red

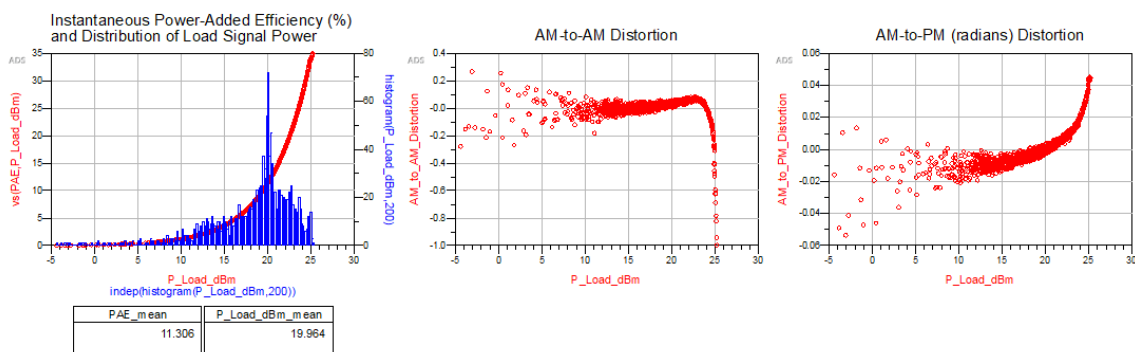


Figure 4.8: Simulation of the Power Amplifier with a Fixed Drain Bias

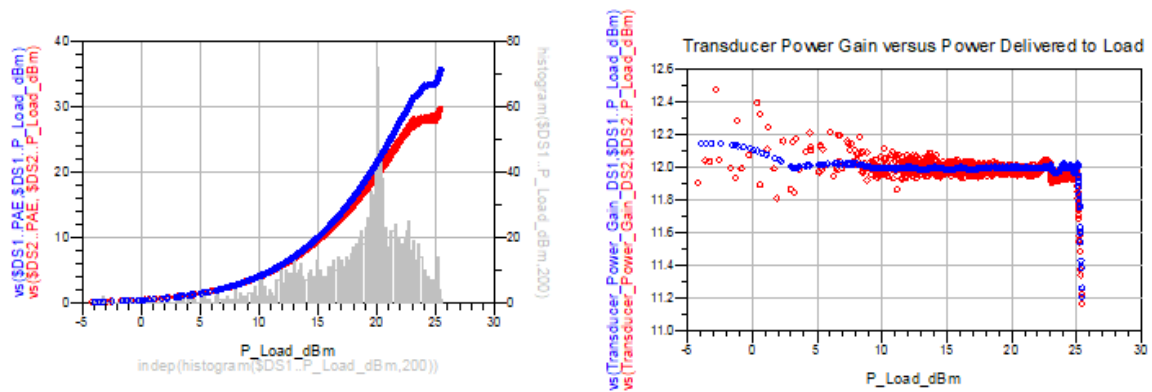


Figure 4.9: Result after ETPA Applied

curve data are from the simulation with a fixed drain bias. The blue curve data are from the envelope tracking simulation with the gain held constant at 12 dB: In figure 4.9, the improvement in PAE is almost 70%. As the load signal power rises, the ET PA's efficiency (blue curve) rises from a low starting point to over 70% at its higher power levels (25dBm). When envelope tracking is used, PAE is greater. Transducer Power Gain of ET And Fixed Bias without ET Is Shown. Throughout the range, the blue line stays above the red line, which was the fixed bias amplifier's gain, indicating that the gain of ET is higher than the fixed bias amplifier's gain. The transducer amplifier's ET power gain is displayed as a function of the power applied to the load by the blue line; the gain is greatest at low power levels and diminishes with increasing power.

AM-to-AM Distortion: Figure 4.10 illustrates the linearity quality of ET PA. The blue curve shows a rather steady AM-to-AM response up to roughly 25 dBm of power applied to the load; after that, gain compression is observed. At higher power levels, the Blue curve (ET Curve) shows somewhat greater gain constancy (less compression) than the red curve.

AM-to-PM Distortion: As we Observe from Figure 4.10 Both blue and red show negligible AM-to-PM distortion up to roughly 10–20 dBm. Particularly at higher power levels, the blue curve (after ET is applied) has somewhat less phase distortion overall than the blue curve.

Instantaneous EVM (%) vs. Time: According to the EVM vs. Time result observa-

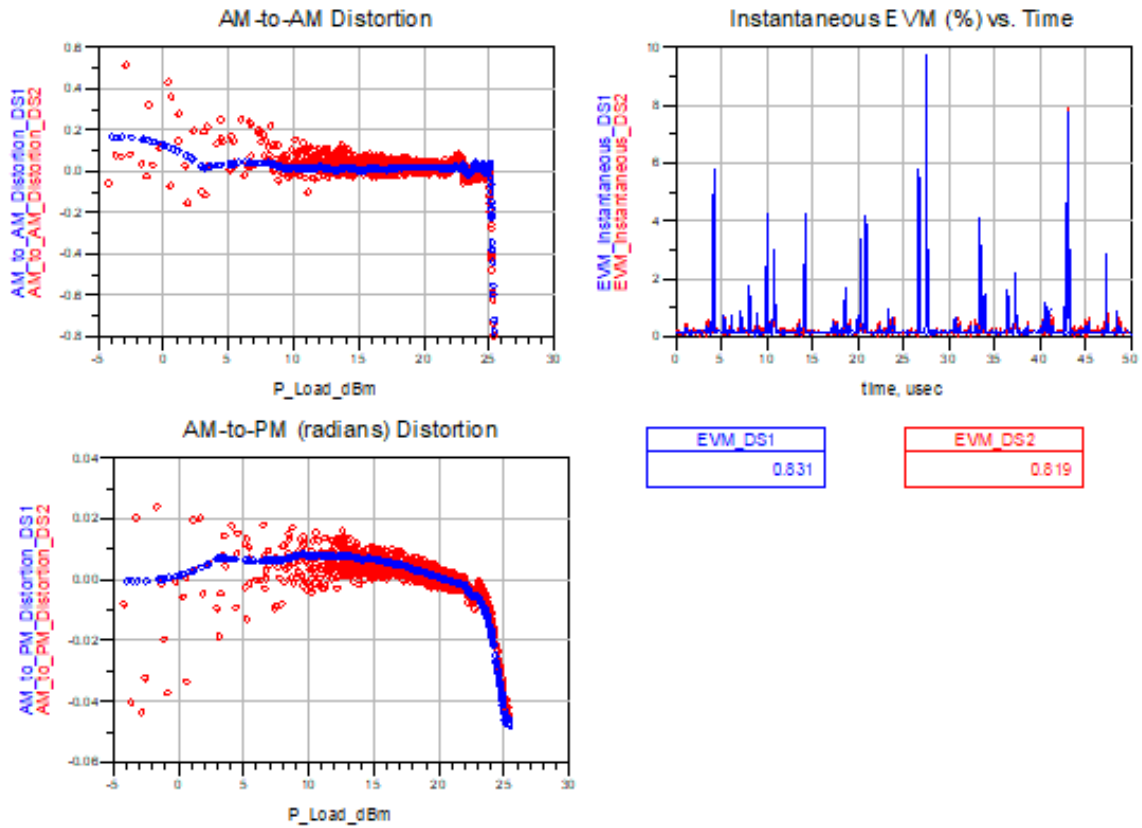
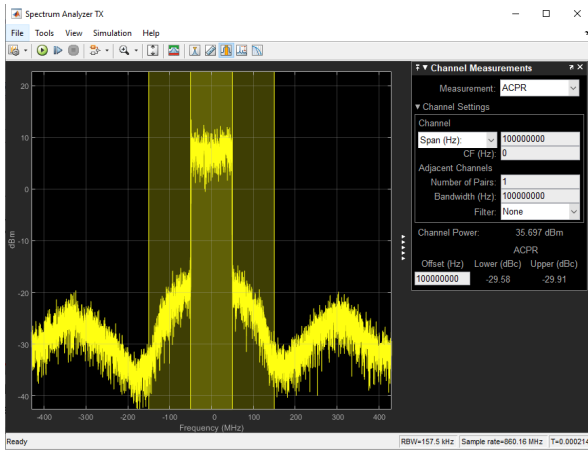


Figure 4.10: Linearity Of Envelope Tracking PA

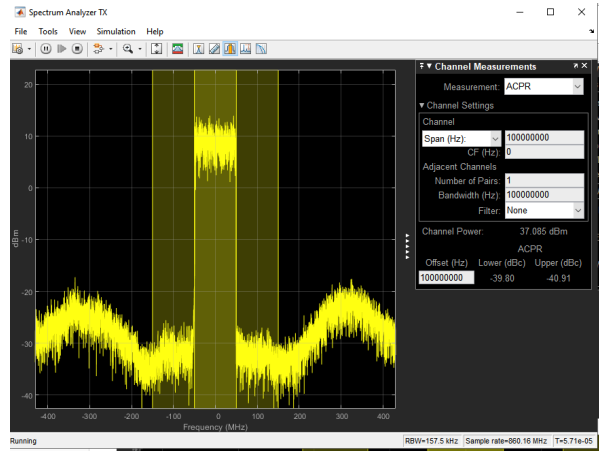
tion, DS1 (blue) has a higher EVM average (0.831%) than DS2 (red, 0.819%). DS2 has improved overall linearity and performance over time, as seen by smaller and more consistent EVM spikes.

4.4 Digital Predistortion for Compensation of Nonlinearities in Power Amplifiers

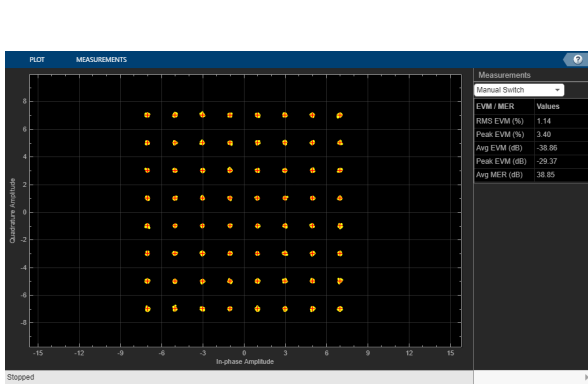
We examine the impact of digital distortion on these findings. how power amplifiers' nonlinearity is improved by the DPD. This simulation employs an LDMOS Doherty PA with an operational frequency range of 3.2-3.8 GHz in order to examine the overall characteristics of the power amplifier in the communication system. for this work The 3.8 GHz frequency was chosen because it allows 5G mid-band deployments, ensures realistic PA testing, optimizes Doherty PA performance, and meets industry standards for modern wireless communications. This PA needs a DC bias of 1.4, 1.6, 3, 5, and 29 volts. We use MATLAB Cod to simulate the outcome. Instead of being a two-tone signal, the signal being amplified now has an OFDM waveform similar to 5G. The OFDM modulator in the baseband signal-generating block is where oversampling takes place. We add a subsystem to monitor the EVM and MER of the amplified OFDM waveform, and the spectrum analyzer analyzes ACPR rather than TOI. Figure 4.11a shows that the system achieves an average modulation error ratio of 24.4 dB without DPD linearization, while Figure 4.11c and Figure 4.11d's constellation plot measurements show that the ACPR is -29.58 at its lower dBc and -29.91 at its upper dBc. Toggle the manual switch to activate the DPD algorithm. Figure 4.11c shows that when toggled, the average MER is greatly increased to 38.85 dB. DPD has this effect. The ACPR is -39.80, which indicates its lower dBc, and -40.91, which indicates its upper dBc.



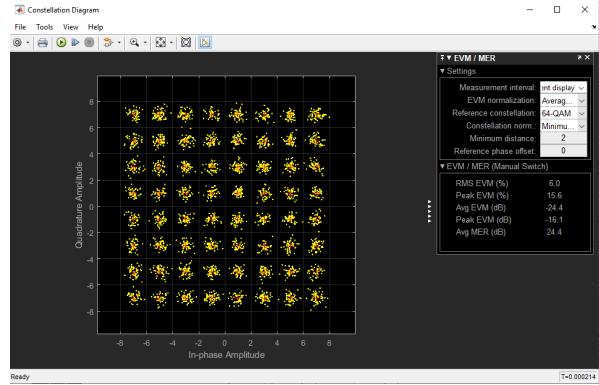
(a) ACPR Without DPD



(b) ACPR With DPD



(c) MER After DPD



(d) MER Before

Figure 4.11: Simulation result of MER, ACPR With DPD and Without DPD

4.5 Comparative Statement

4.5.1 The Power Amplifiers Results of this work vs. 5G Power Amplifier Performance

Frequency:- The frequency bands for 5G mobile networks are divided into two ranges: mm-Wave, which spans from 25 GHz to 53.6 GHz, and FR1, sometimes referred to as sub-6, which spans from 800 to 6 GHz and is suitable for wireless communication in rural areas [43]. For this research, we select the mid-band frequency range which is Sub-6 GHz. We selected this frequency range because different frequency bands in 5G networks are used for various functions, including data rates, capacity, and coverage. It's critical to examine how power amplifiers (PAs) behave throughout a range of frequency bands since their performance changes with frequency owing to impedance matching, efficiency, gain, and linearity. Since several bands are used for various network requirements in a real-world 5G deployment, utilizing only one frequency would not give a complete picture of how the PAs function.

Power-Added Efficiency: For base station applications particularly in 5G Networks power amplifiers usually target PAE values of 50% to 75% in order to handle the high power consumption requirements in densely packed networks [44].

Performance results of Doherty PA PAE of this work are up to 71.98% and for ET PA 70%. Provide results that are very appropriate for 5G applications, with efficiencies that surpass normal lower-end predictions. Though still respectable, Class-AB PA's achieve a PAE of 52.76% in this work.

Output Power: 5G networks often require output power in the 20–40 dBm range for optimal coverage in the 800 MHz–6 GHz frequencies. To accommodate broad coverage and manage intricate modulation systems with high peak-to-average power ratios, it is usually between 35 and 50 dBm. Both the Doherty PA, which achieves 36.543 dBm, and our Class-AB PA, which achieves 30.00 dBm, effectively meet these power needs, which are comparable to those of 5G base stations. Even with its lower output power of 25 dBm, our ET PA manages to achieve remarkable efficiency [45].

Gain: In 5G networks, High gain helps to amplify weak signals while maintaining quality, with typical gain values around 10-12 dB in 5G PAs [46]. With a gain of 17.76 dB,

The Class-AB PA is better capable of amplifying signals than the ET PA (12 dB) and the Doherty PA (12.543 dB). These lower gain values are still within the permitted range for effective 5G operation, even if they may restrict the amplification performance.

Linearity: In order to preserve signal integrity, 5G networks must have exceptional linearity, especially for high data rate applications. Techniques like envelope tracking and digital pre-distortion are used to enhance linearity [44]. Techniques like AMPM correction and amplitude modulation are crucial for minimizing distortion. By removing Amplitude Modulation to Amplitude Modulation distortion and improving signal quality, our ET PA solution demonstrates excellent linearity performance and fits in well with the high linearity requirements of 5G networks. The Doherty PA shows good linearity with an EVM of 29.37 dB and an adjacent channel power ratio of -40.91 dBc. This is satisfactory, but more tuning may be necessary for higher-order modulation schemes in 5G. However, when the input power grows, the Class-AB PA experiences greater linearity problems and increases AM-AM distortion, which may deteriorate signal quality in higher modulation forms that are characteristic of 5G.

Table 4.1 and Table 4.2; Show the comparison of the power amplifiers performance metrics values in 5G networks and power Amplifiers performance metrics values for this research.

Table 4.1: Performance range of power amplifiers (PAs) for 5G networks

Parameter	Typical Range for 5G PAs; [47] [48]	Comments
PAE	45% - 75%	Higher efficiency using GaN-Doherty and ET advanced PAs
Output Power	20 dBm - 50 dBm	3 to 100 Watts for wide-area and macrocell applications
Gain	10 dB - 15 dB	Ensure adequate signal amplification
Linearity	High (Techniques Applied)	DPD and Envelope Tracking techniques improve linearity

Table 4.2: The Result of PA's In this Research

Parameters	Class-AB PA	Doherty PA	EVT PA
PAE	52.76 %	57.318 % @ 1 GHz; 71.982 % @ 800MHz	70%
Output Power	30.00 dBm	34.500 dBm @ 1GHz 36.543 dBm @ 800MHz	25.00 dBm
Gain	17.76 dB	12.543 dB	12 dB
Linearity	AMAM Increased with Increased Psource. AMPM Values Varies ; But are within a manageable Range.	ACPR -40.91 dBc and EVM 29.37 dB AM-PM decreases as RF power increases	EVM of ET PA is 0.83 AM-AM Improved

Chapter 5

Conclusion and Future work

5.1 Conclusion

A thorough analysis of Class AB-PA, DPA, and ET PAs for a large MIMO 5G network has been provided. With a frequency of 1 GHz, the Class AB power amplifier has a power gain of 17.16, a PAE of 52.76%, and a power delivery of 30.414. therefore when we operate at the low frequency of 850 MHz, this amount will decrease. A transducer gain of 9.987 dB with a minimum gain compression of 0.999 dB was demonstrated, exhibiting a balance between linearity and efficiency.

Efficiency of a Doherty Power Amplifier When operating near maximum efficiency, the Doherty amplifier outperformed the Class AB amplifier with a higher PAE of 71.98% at high power levels. Power Delivered: A maximum power of 36.54 dBm was delivered to the load, with the load impedance adjusted to provide the best possible trade-off between efficiency and power. Doherty PA Linearity: Although the Doherty PA was quite effective, its linearity was somewhat hindered, especially at high power levels, as shown by the AM-to-AM distortion and gain compression charts.

ET PA Efficiency of Envelope Tracking Power Amplifier With PAE values ranging from 19.902% to 21.888% and an overall PAE of 70%, the Envelope Tracking (ET) PA has a dynamic efficiency that varies depending on the dataset and operating conditions. At high output power levels, efficiency gains were observed due to the ET technique. We looked at AM-to-AM Distortion in terms of Linearity Property. Despite achieving a high linearity, AM-to-AM distortion was low until 20 dBm but increased sharply at power

levels beyond 25 dBm, suggesting that signal quality may be compromised at peak power. Additionally, we examine the function of digital pre-distortion techniques and ACLR optimization for Doherty PA. Doherty PA operates at 3.6-3.8 GHz with a gain of 29 dB. Following the application of DPD to the Doherty power amplifier, the system's MER improved significantly to 38.85 dB, as shown in Figure 4, and its ACPR decreased from -39.80 lower dBc to -40.91 dBc, as shown in Figure 3.

Each of the PAs discussed in this paper has unique performance traits. Theoretical study and Comparison were done with the test Simulation result Of PAE Vs output power. Additionally, use ADS software to compare output power to gain. For this paper, the way to conduct all essential performance metrics such as Output power, linearity, gain, and PAE for Three power Amplifiers are explained. The advantages and disadvantages of Class AB, Doherty, and envelope-tracking power amplifiers in terms of efficiency, gain, output power, and linearity for 5G networks have been clarified by a comparative comparison. Although each architecture has benefits, the Doherty and Envelope Tracking Power amplifiers seem to be better choices because of their superior linearity, efficiency, and gain.

While the efficiency and linearity of the ET PA are balanced, distortion increases at high output. Doherty PAs perform well for high-power and high-efficiency applications, like 5G base stations. The envelope-tracking power amplifier is ideal for applications that require dynamic efficiency modifications, even though linearity becomes a problem at high power levels. Overall, the Class AB-PA is a good choice for situations where the least amount of distortion is required and suitable for applications requiring linearity and modest power. These findings provide engineers and researchers with important direction when choosing the best power amplifier for effective and high-performance 5G communication systems.

In conclusion, the ET PA is a strong candidate for 5G networks, particularly for applications that value energy efficiency and signal integrity, because of its superior linearity and efficiency performance. The Doherty PA is a good option for 5G deployments because it achieves a good balance between linearity, efficiency, and output power. Keep in mind that the Doherty Power Amplifier is put through multiple frequency range checks. While the Doherty and ET PAs are both well-suited to the performance needs of 5G networks, the Class-AB PA may require optimization to meet the more demanding specifications

of modern 5G installations. The Class-AB PA may be more appropriate for older or less demanding applications within the 5G ecosystem due to its lower efficiency and linearity.

5.2 Future work

Building on the knowledge acquired, a number of study avenues are recommended for the future:

Advanced Amplifier Architectures: To further maximize performance for 5G and beyond, look at cutting-edge amplifier technologies, such as hybrid designs that combine Doherty and ET methods.

GaN-Based Power Amplifiers: Examine how to improve PA designs for 5G massive MIMO systems by utilizing Gallium Nitride (GaN) transistors, which provide exceptional efficiency, thermal performance, and high-frequency operation.

Broadband Operation: To ensure compatibility with high data rates and spectrum efficiency, broaden the scope to include examination of PA performance across larger bandwidths characteristic of future 5G and 6G networks.

Thermal Management: To solve the thermal issues related to high-power amplifiers in huge MIMO arrays, research innovative cooling methods and materials.

Machine Learning for PA Optimization: Create AI-based algorithms to maximize performance metrics in real time, including as linearity, distortion correction, and efficiency.

Future power amplifier designs can attain more efficiency, better linearity, and greater reliability by incorporating these developments and utilizing GaN transistor technology. This will guarantee the successful deployment of high-performance 5G and 6G networks.

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