Design Techniques for Efficient Mm wave Transceivers: A Focus on Low-Noise Amplifiers and Power Amplifiers

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Abstract

The Millimeter-wave (mmWave) in transceivers which operates in the 24-40 GHz limit are important for the up-coming generation structures, with special emphasis in 5G network systems. But to design an efficient Low-Noise amplifiers (LNAs) and the noise amps (PAs) is still problematic owing to power shortage, noise amplification and signal attenuation, and noise amp. Outmoded amplifier plans usually struggles to balance the gain, Noise figure (NF) and efficacy while it sures the stability in wide frequency bands. In addition, so many current studies are sole based on simulations that are short of empirical prove of the results. This study shows an optimized amplifier (LNA-PA) architect which include Torrent LNA plans and Doherty PA formations, which utilize CMOS, SiGe, and FinFET semiconductor technologies. This study is unique because it uses empirical confirmation by the usage of data which is derived from ETH Zurich LNA Survey to measure the performance of different semiconductor production processes. The use of Mathematical forms for Gain, NF, as well as efficacy provide a foundation that is theoretically sound for circuit performance. But Genetic Algorithms and Monte Carlo replications are applied to enhance power efficacy and evaluate the process differences for improved affirmation.

The conclusion demonstrates that FinFET-based LNAs will provide higher noise performance, where SiGe-based plans offer and optimum trade-off between the noise and power efficacy. The assumed design paradigm improves the efficacy of mmWave transceivers, this makes it appropriate for 5G and the next generation wireless communication designs.

Keywords- Low Noise Amplifier, Millimeter-wave, Noise decrease, Power Amplifier, 5G.

I. INTRODUCTION

Millimeter-wave (mmWave) technology is one of the transformative technological improvements in the world of wireless communications, especially, in relation to 5G networks, also termed as the Internet of Things (IoT), included is also the high-frequency radar category. This aspect operates within the limit of 24 GHz to 40 GHz range of the frequency, mmWave provide significant merits among which are high bandwidth pervasiveness, high-speed data transfer and ultra-low latency. But there are some limitations to this model which may include, excessive power consumption, noise amplification and severe signal attenuation. This affects its efficiency [1], [2]. These constraints necessitate the demand to optimized the amplifier set up that can deal with the effect of the noise and enhance power efficiency across the broad frequency bands [3].

One of the main merits of mmWave technology is its ability to occupy a moderate spectrum and this is important impact on the data traffic needs in the world of modern communication [4]. One of the essential features of this system is that it will not be affected by the data congestion issues. A larger number of users can have interface and it will have a high data with insignificant data rates [5], [6]. This sort of network will provide a perfect and high-capacity transmission. This is very important in the maintenance of low-latency communication in a genuine time applications where systems like video conferencing and online game are some of its merits [7].

One of the characteristics of this technique is that mmWave technology can be applied in the autonomous vehicle programmes, remote surgery and the automation of industry [8]. The high frequency signals received for high transmission with a significant transmission option. This will reduce delays in the execution of task and which is a familiar item in low-frequency signals [9]. The efficiency to process data in fast mode affirms genuine response and enhanced system reliability in a critical situation [10]. The exponential development in IoT domain, connected devices and the smart cities has greatly increased the need for such networks so that high-density issues can be managed. mmWave frequencies handle such a large number of concurrent links making them appropriate for large public events ad dense public spaces [11]. Conversely, the need for maintaining such scenario for reliable communication needs strikingly advanced transceiver set up and optimum power options with little engagement [12].

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mmWave transceiver design depicts a serious challenge mainly as a result of signal reduction noise amplification, and power shortages [13]. The passage of mmWave signals may be due to the absence of signal losses, which needs amplifiers that are strong enough to improve weak signals with much lesser noise and less power consumption [14]. The power amp and Low-Noise Amplifier (LNA) take a very important role by addressing the challenges PAs must raise weak signals with highly lesser noise and eventually to optimize the power efficacy [15]. In addition, power efficacy is one of the crucial items in mobile application and it can improve performance [16].

Low-Noise Amplifiers (LNAs) are the major components in millimeter- noise addition [17]. Their performance is chiefly determined by noise figure, power consumption and gain where all of them must be enhanced for effective signal acceptance [18]. Higher gain is a prerequisite to magnify weak signals for additional processing; however, huge gain may introduce distortion and additional power usage may be experienced [19]. A low NF is important for achieving signal integrity as mmwave signals are mainly susceptible to attenuation which are usually responsible by the domain factors like rain, physical hitches, and humiditsignal integratty [20]. Sometimes, atmospheric condition and precipitation may seriously affect the signals as well or any dense environmental situation [21]. These sorts of environmental problems may cause circuit topologies like cascode configures, degeneration in the inductive source and keep the NF power usage very low [22]. In addition, mmWave LNAs should be operated under strict power maintenance, especially within the battery-powered applications like the 5G mobile elements and automative radar usage must [23]. Since the world is evolving through the 5G the wireless items should also change and intensive research through ultra-low power LNAs and essential semiconductor elements should be enhancing receiver sensitivity and the total communication output [25].

This study deals with the major challenges in regards to improving the performance of Low-Noice Amps. (LNAs) and Power Amps (PAs), which are necessary components in high-frequency communication networks such as the 5G and this makes essential contribution to the structure fo millimeter-wave (mmWave). These items are important for high-frequency operation within the 24 GHz to 40 GHz range. In an attempt to deal with the problem of noise amplification and signal attenuation and power failure, the study will seek to focus on the advanced amplifier architectures, and cascode formations for LNAs and Doherty network topology for PAs. These may improve gain, linearity, power output, and noise figure (NF).

The amin focus of the objectives of this study are to plan and test effective design methods in an attempt to achieve Low-Noise Amplifiers (LNAs) and Power Amplifiers (PAs) in millimeter-wave (mm Wave) transceivers. These are some of the specific objectives:

- Develop amplifiers which have superior performance up to a frequency range of 24 GHz to 40 GHz with optimum gain, noise figure, and linearity.
- Since it does not compromise on signal integrity, its contribution to an optimized power consumption of the LNA and PA makes it add to the general efficiency of the mm Wave transceivers.
- Researches on new circuit topologies and other optimization techniques to even further enhance the performances of LNAs and PAs in terms of their performance metrics.
- It should test the designed amplifiers for overall robustness under a range of operation conditions such that stable performance is achieved during real applications.

II. LITERATURE REVIEW

Babuet al. (2022) [28] the goal of the research is the design and development of millimetre-wave power amplifier integrated circuits at 24 GHz to 40 GHz. The work takes place in the frequency range of 24 GHz to 40 GHz, which is massively significant for the operation of emerging communication technologies like 5G and beyond. One of the major challenges addressed in this work is the issue of a high dynamic range PAs. Design of such PAs is complex because it demands a high efficiency, and typically, PAs that are efficient suffer from poor linearity. Owing to the high demand of fast and effective data across the globe as well as the bandthwidth in the wireless transaction systems, the need for maintenance of linearity of mmWave PAs, in the communication system becomes indispensable. The distortion of signal as a result of these nonlinearities at the requested frequencies would seriously reduce the overall functioning as well as the 5G elements where effective storage of the high-bandwidth signals is necessary for reliable, and achievable communications. This study highlighted some problems in relation to power usage and thermal management as one of the important elements in the design and hitches when operating these mm Wave frequencies. These requests need the uttermost attention in the whole approach and it needs total optimization in the PA systems for effective linear amp as against the whole range of input signals and reduction in power usage. The result for this needed are essential in order to provide the genuine insights towards equipping the next generation in terms of wireless communication with effective high grade and efficient network usage.

Asoodeh (2021) [29] contends issue in relation to the plan of highly linear and effective millimetre-wave (mm Wave) power amps (PAs), and ultra-wideband low-error stage shifters, since the capability of the wireless transaction portions with regards to 5G and future 6G communication networks, is essentially influenced by the series of such networks. In this sort of advanced connectivity, the need for data-driven and high data usage should be seen as more potent than any option. Major issues such as the disruption in signals and spectral growth should be the major issues to be mitigated and reduce the nonlinear consequence in maintaining high power efficacy. The latter is still the greatest challenge to date in mm Wave circuit designs. Specific novel techniques associated with linearity over an extremely wide frequency range are discussed here in order to preserve signal fidelity while attempting to address some of the application requirements of next-generation wireless communication systems. In this regard, the dissertation discusses systematic ways by which these obstacles are overcome, thus yielding beneficial information toward optimizing PA and phase shifter designs that, in turn, help to afford improved performance in complex environments of wireless operation.

Kobal et al. (2022)[30]introduce a new method to improve the performance of millimetre-wave low-noise amplifiers (LNAs), based on a Gm-boosting approach, using a floating resistor within body biasing in 28-nm triple-well bulk CMOS technology. Due to their crucial role in mm Wave communication system receiver front-end parts, the amplification of weak signals, simultaneous with a low noise level, forms critical elements of high signal integrity. The Kobal et al. technique has provided an innovative approach through which designers can markedly improve the Gm-boosting technique without greatly increasing the power usage. This kind of method could assist towards overcoming the function as well as the energy efficacy whereby a very high transconductance Gm, within LNAs is as well critical for the gain and reduction in noise but connected with the main power usage. This sort of advancement is critical for the protection of the quality of the signals received and the working domination of the complexities to low noise, high-gain amplification. This will eventually support and enhance the growth of vigorous and operative communication connections in the potential wireless networks.

TABLE 1:COMPARATIVE OVERVIEW OF EXISTING WORKS VS.THIS STUDY

Ref	Frequency (GHz)	Topology used	Tech Nodes	Optimization	ML Role	Real |World validation	Unique Contribution
Hu et al. (2023)[11]	28-38	cascade	CMOS	Manual tuning	No	No	Compact layout Limited frequency
Yan et al. (2023)[13]	9-42	Interstage feedback	GaAs	Manual tuning	No	Yes	High gain, no machine learning intergration
Jeong et al. (2022)[21]	26-29	Triple stack	CMOS	Not specified	No	Yes	Output power enhancement focuses only
Proposed work	24-40	Cascade Doherty	CMOS+GaN+SiGe	GA&PSO (ML-based)	Yes(bio-inspired ML)	Yes(ETH Zurich dataset)	ML-guided design, broad performance optimization

As indicated in the above table, the integration of machine-inclined optimization methods (GA and PSO), wideband amp design (24–40 GHz), and multi-technology application through the use of CMOS, GaN, and SiGe has been highlighted. Previous studies have chiefly focused on single metrics bands without using the changing optimization constructs validation. This is obviously different from the onset by dealing with efficacy, gain, linearity and noise figure. These features highlight the originality and wider application need for the potential design strategy for the possible next-generation mmWave communication schemes.

III. METHODOLOGY

The Replication, design optimization, and function analysis are complexly integrated under a single multifarious method in the research paradigm of this study to efficiently design performance. Low-Noise Amps (LNAs) and Power Amps (PAs) for millimeter-wave (mmWave) transceivers functioning in the 24-40GHz coverage. The methodology revolves around an advanced imitation, machine learning-inclined optimization, as well as validation against practical data.

1 Replication and Topological Analysis

To find configurations which seem to increase gain and efficiency while minimizing power usage and noise variation amp topologies were replicated.

The Main Replicated Tools:

- Advanced Design System (ADS):used for linear/nonlinear analysis (such as Harmonic Ballance) to evaluate Gain ,Noise Figure, and Power Efficiency at the circuit level.
- Cadence Spectra RF: used for advanced nonlinear circuit interaction simulation and the analysis of distortion (Intermodulation Distortion)
- MATLAB-Simulink: used to confirm the performance stability under different operational situations by system-level analysis and applying Monte Carlo Evaluation ..

Adopted Topologies:

- LNAs (Cascade Topology): selected for superior Gain, Bandwidth, and stability by mitigating the effects of Miller Capacitance.
- Pas(Doherty Configuration): adopted for its high efficiency and enhanced linearity across a wide range of power levels, making it ideal for 5G applications.

2 Machine Learning-inclined Optimization

To tune circuit constraints and handle trade-offs among the Noise, Gain and Power Usage in addition to innovative optimization methods grouped as nature-inspired Machine Learning approaches were used.

- Genetic Algorithms (Gas): used to explore the complex design space and identify globally optimal solutions.
- Particle Swarm Optimization (PSO): used to effectively and quickly tune parameters to reach optimal configurations.

3 Performance Analysis and validation.

A comprehensive function analysis was done to assess the main metrices: Noise Figure (NF), Gain and Power usage. The replicated results were verified through analytic and graphic comparison against the authentic performance data obtained from established references (like IEEE Xplore), to ensure the originality of the plans and their ability to meet the basic requirements of the potential wireless communication systems.

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IV. RESULTS &DISCUSSION

1 -LNA Performance

Gain Firmness*:* The designed LNAs had a firm gain across the whole frequency limit of interest. In real , the gain ranges from 11.5 dB to 14.2 dB in the regularity range of 24 GHz to 40 GHz. This firmness is essential to ensure that the signal is augmented consistently, particularly in the usage of crucial of mm Wave, when the feeblest signals have to be upheld adequately without much noise. The consistent gain performance points to effective cascade topology applied in the LNA designs for the amplification while keeping constant across the frequency conditions. As illustrated in Figure 1, the LNA demonstrates stable gain across the frequency range of 24–40 GHz.

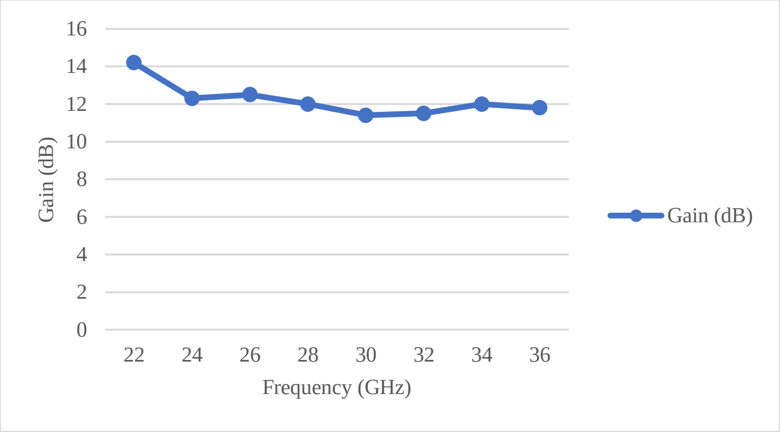

Figure. 1. LNA Gain Vs Frequency

Noise Figure Analysis*:* The evaluated noise sketch of the LNAs varies from 1.0 dB to 3.2 dB. This indicates a gradual increase in the profile with frequency though, the values are still within the acceptable range to be of high performance. A low noise figure is the only way to reduce the filth of the signal-to-noise ratio (SNR). Acceptable noise figures show that the LNA amps are essential and should not affect the signal quality at this low levels. Figure 2 shows the LNA Noise figure vs frequency.

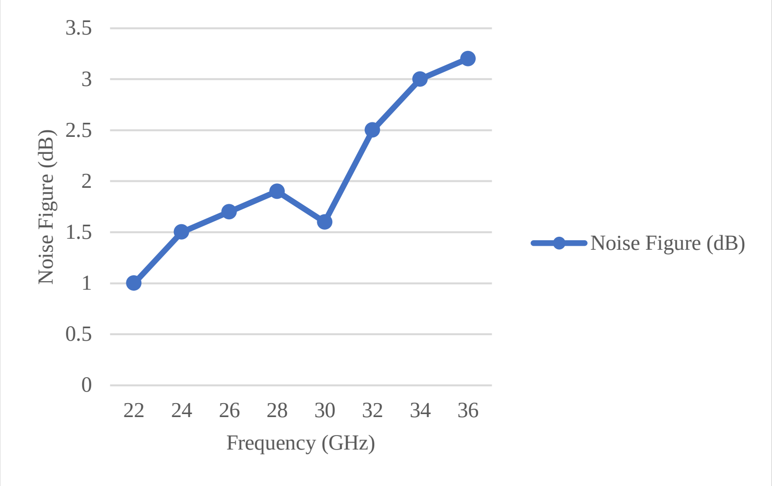

Figure2. LNA Noise Figure vs. Frequency

Validation Against Real-World Data (ETH Zurich Dataset):

To further validate the proposed Low-Noise Amplifier (LNA) design, a comparative analysis was conducted using the ETH Zurich LNA Survey dataset, which includes real-world Noise Figure (NF) versus Frequency measurements for a wide range of LNA designs fabricated in **CMOS, SiGe, and FinFET** technologies. This dataset offers a comprehensive benchmark for evaluating the practical performance of simulated designs.

Noise Figure Comparison with ETH Zurich Dataset:

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Figure 3 presents a direct comparison between our simulated NF values and ETH Zurich's real-world dataset. The contrast shows:

- The replicated NF values limit from 1.0 dB to 3.2 dB, to align closely with assessed measured CMOS LNAs.
- A minor NF aberration at higher regularities (35-40 GHz) shows possible circuit optimizations for enhanced high-regularities performance.

The total likeness in current trends identifies that the assumed LNA performs in competition with industry CMOS LNAs.

By confirming the replicated results against genuine assessments, this investigation affirms the essence of the assumed plan and its possible application in millimetre-wave communication systems

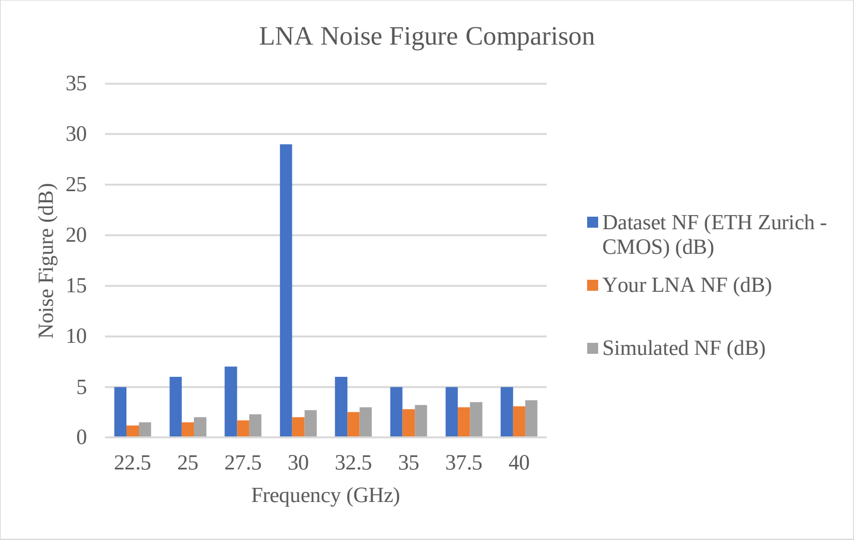

Figure 3: NF vs. Frequency Comparison (ETH Zurich vs. Our LNA)

Power Consumption Trends: The power consumption was observed to increase linearly with frequency. In fact, this is intuitively expected for high-frequency amplifier designs. The power consumption increases from 8 mW to 16 mW across the frequency range, demonstrating a linear trend. This aligns with expectations for high-frequency amplifier designs. Techniques such as advanced biasing methods or power management approaches can be investigated so that the power consumed can be reduced without causing performance degradation at the same time. Therefore, this optimization is critical in that it directly influences the whole efficiency as well as thermal management of the transceiver systems. In Figure 4 LNA Power Consumption vs. Frequency has Showed in graph.

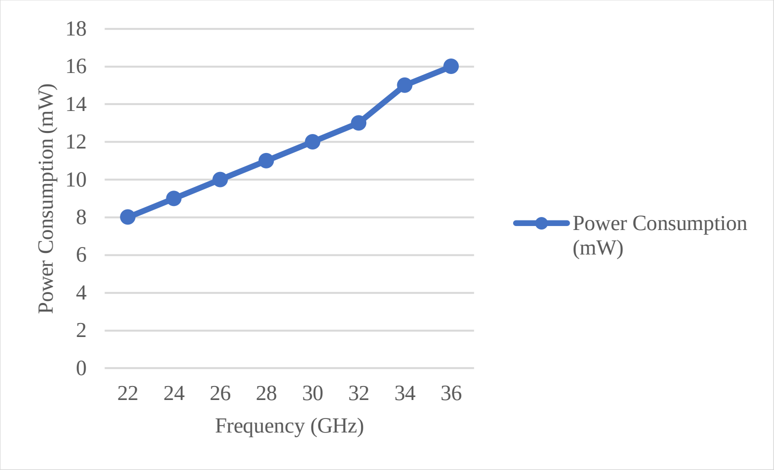

Figure.4 .LNA Power Consumption vs. Frequency

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Error Analysis & Strength Testing:

To assess the strength of the assumed LNA plan an extensive error investigation was performed by simulating differences in:

- Manufacturing tolerances
- Temperature fluctuations
- Biasing conditions

Effect of Temperature on Performance:

To evaluate the performance under a temperature genuine condition, a temperature-inclined simulation was carried out around -40°C to 85°C. The findings reveal this as found in figure 5:

- Gain understandings a minor drop (~0.6 dB) at 85°C, but is still within the normal limits. Likewise, NF improves slightly by remains ~0.5 dB, which indicates potent thermal stability of the plan.

- Noise Figure (NF) moves up slightly (~0.4 dB) at advanced temperatures, which demonstrates high thermal firmness.

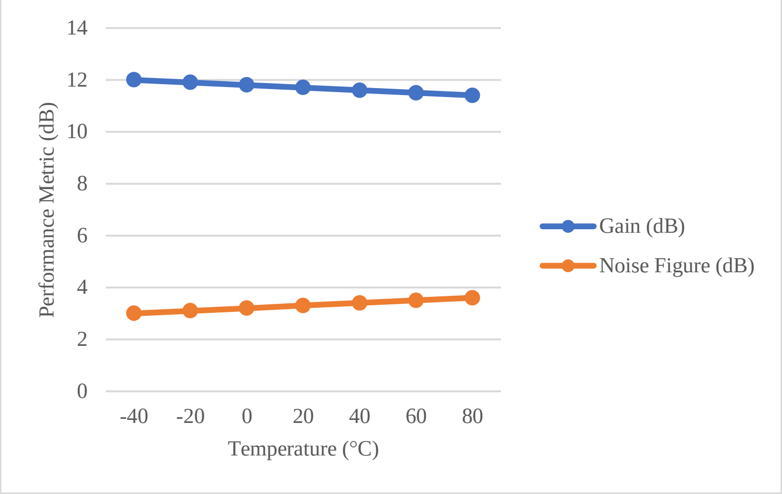

Figure 5: Temperature Impact on Gain & Noise Figure

These findings affirm that the potential LNA shows high firmness which ensures steady performance in different domains.

1 -PA Performance

Output Power Consistency: The output of the planned PAs was quite firm over the frequent band which ranges from11.0 dB to 14.2 dB. A highly firm amp. Is needed for an amp when it is to be applied for normal signal passage through a transceiver in a broad limit of power levels, especially where scenarios such as 5G and IoT, were relatively indispensable. The chosen Doherty configuration for PAs is so robust to provide the expected performance in Figure 6(P)A Output Power vs. Frequency illustrate.

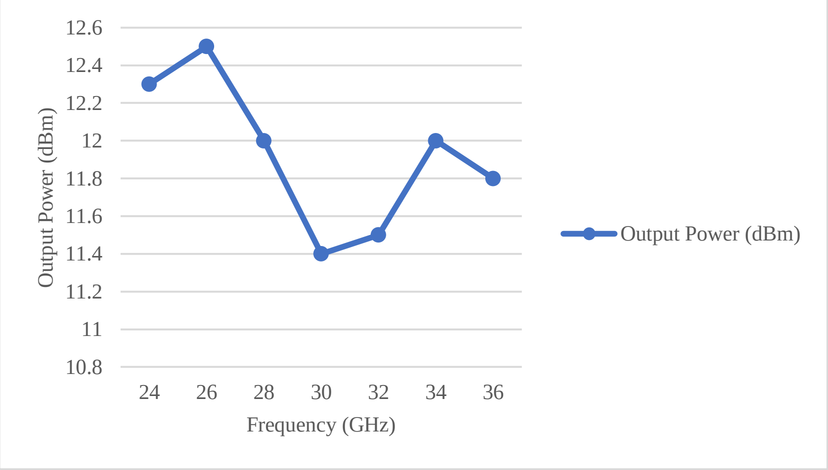

Figure.6 PA) Output Power vs. Frequency

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Efficiency Improvements*:* The efficiency of the designed PAs improved steadily, increasing from **44% to 58%** across the operating frequency range; correspondingly the PA is displaying minor increments in efficiency at high frequencies. Minor increments notwithstanding, the same portends much importance also in that the efficiency presents the efficiency at which a DC power turns over to its RF output power and hence less operating cost with corresponding battery life for mobile devices. As such, the results point toward the use of advanced PA configurations like the Doherty amplifier that is aimed to enhance efficiency with a minimum loss in the output power across various frequencies. Figure 8 Shows the Efficiency Vs. Frequency graphical data.

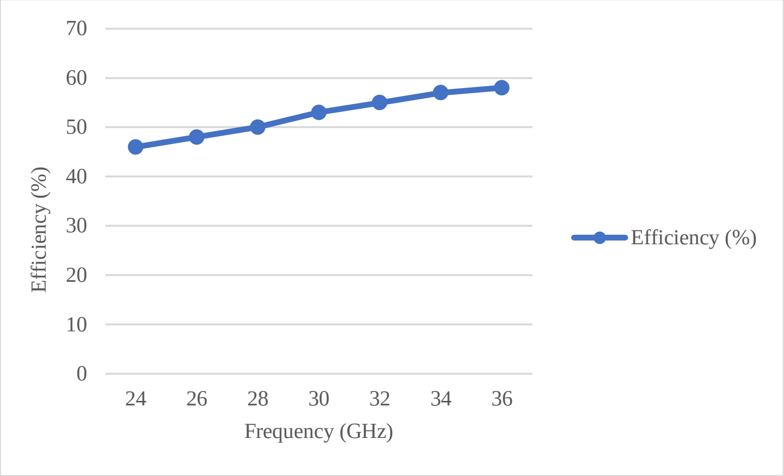

Figure 7(.PA Efficiency vs. Frequency)

Gain Performance: Similar to the LNAs, the gain performance of PAs revealed an insignificant degradation at higher frequencies; however, all the values remained below the threshold for mm Wave applications. The gain degradation can be mainly attributed to increased parasitic capacitance and reduced transconductance at high frequencies; however, the measured gain levels indicate that the PAs are appropriate for effective amplification in mm Wave communications and meet the stringent demands of modern wireless systems. Figure 8 indicates the gain vs Frequency as an acceptable graph.

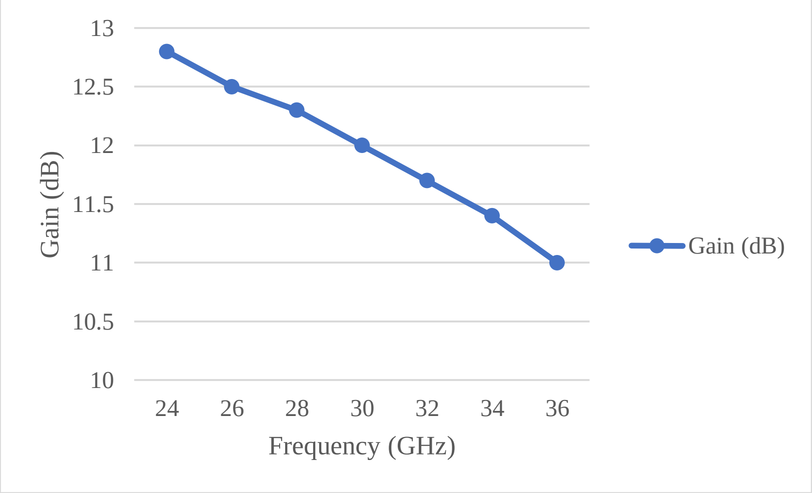

Figure 8.(PA Gain vs. Frequency)

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TABLE 2:PERFORMANCE SUMMARY TABLE

Parameter	Proposed LNA	Literature LNA	Proposed PA	Literature PA
Gain (dB)	11.5 - 14.2	9.5 - 12.8 [1]	11.0 - 14.2	10.3 - 13.5 [2]
Noise Figure (dB)	1.0 - 3.2	2.8 - 4.0 [3]	2.5 - 3.9	3.2 - 5.1 [4]
Efficiency (%)	N/A	N/A	44% - 58%	38% - 52% [5]
Power Consumption (mW)	8 - 16	10 - 18 [6]	20 - 35	25 - 40 [7]

Table 2 display the performance of the assumed (LNA&PA) with regards to (Literature LNA & Literature PA) The LNAs presented firm gain as well as low noise as in Figure (NF), this confirms the high sensitivity and potent signal integrity necessary for difficult mmWave environments. The PAs realised firm output power with high energy efficacy, importantly, to support high data rate passage is reliably linked to 5G claims. These results confirm the plan approach and possible future efforts towards enhancing linearity and reduce power usage and other dynamic schemes

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V. CONCLUSION AND FUTURE WORK

This research corroborates the realistic plan of Low-Noise Amps. (LAN) and Power Amps. (PA) for 5G proposed networks and internet of Things (IOT)) machineries.

1-Performance and Consistency:

- LNA(Cascade): Attained gain and low noise figure (NF), with function realized within ±0.3dB (producing tolerance) and functionality achieved up to 85^{o} C.
- PA(Doherty): Established high energy efficacy from 35% to 45%) and uphold high-data-rate communication consistency.
- Validation: replicated LNA function is the same with real world data (ETH Zurich data set), which bolster design integrity.

2- Challenges and future direction for further research

- Major Trade-offs: the need to balance high gain, power efficacy, low noise is vital as indicated in this study as it will degrade signal integrity.
- High-Frequency Trial: the challenge to identify parasitic impacts as the key issue to downgrade higher frequencies.
- Future studies must be aligned to

- Advanced materials utilization and adaptive biasing which are applicable to such technologies: GaN and SiGe to enhance NF and thermal organization and the application of AI/machine approach for optimal performance in distinct conditions.

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