NJRFCS

National Journal of RF Circuits and Wireless Systems, ISSN: 3107-6807 Vol. 3, No. 1, 2026 (pp. 49-56)

RESEARCH ARTICLE

ECEJOURNALS.IN

Design and Performance Analysis of an Envelope-Tracking Doherty Power Amplifier for 6G Wireless Base Stations

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KEYWORDS:
6G base stations,
Doherty Power Amplifier (DPA),
Envelope Tracking (ET),
RF front-end,
GaN HEMT,
energy efficiency,
power-added efficiency (PAE),
mmWave communication,
ADS simulation,
linearity enhancement.

ARTICLE HISTORY:
Submitted : 09.02.2025
Revised : 28.04.2025
Accepted : 20.07.2025

https://doi.org/10.17051/NJRFCS/03.01.07

Abstract

The transition to 6G wireless communication networks requires installation of energy-efficient, high-linearity power amplifiers (PAs) as the base station RF-front-ends to address ultra-high data rates, massive connections, and onerous power limitations. The conventional PA architectures are characterized by low efficiency of the power back-off point which is experienced during power back-off especially under high peak to absolute power ratio (PAPR) waves which appear in broadband 6 g signals. In the efforts to solve this challenge, this paper develops a high-efficiency Doherty Power Amplifier (DPA) architecture with an Envelope Tracking (ET) that will focus on enhanced back-off efficiency and linearity of a 6G base station. The principle aim of the present work is designing, simulating and analysing an ET-enabled DPA implemented with GaN High Electron Mobility Transistor (GaN HEMT) at the 28 GHz mmWave frequency. The suggested design augments a Class-AB principle (load modulation) fundamental amplifier and a Class-C peak amplifier, whereas the ET module adjustably adjusts the drain voltage on an envelope-based correction of the RF signal to decrease power waste in terrain-off differentiations. Circuit level co-design and simulation is employed at both RF behavior, with Advanced Design System (ADS), and dynamic power supply response, with HSPICE simulation, levels. The matching network is matched in order to maximize the power transfer, and the load-pull simulations are applied to receive the best impedance conditions. Simulation results indicate that the proposed ET-DPA paves a way to a peak power-added efficiency (PAE) of 67%, small-signal gain of 13.8 dB and adjacent channel power ratio (ACPR) of -28 dBc. In addition, the amplifier achieves high efficiency (53%) at 6 dB output back-off and represents significant enhancement of conventional DPA designs. To recap it all, during envelope tracking in a Doherty architecture, an immense improvement is noticed in power efficiency and linearity in high-frequency 6G communication systems. The work provides one of the possible design strategies of energy-aware base station power amplifiers working within mmWave bands, as well as that paves the way to experimental verification and real deployment.

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How to cite this article: Rane Kuma R, Sikalu TC. Design and Performance Analysis of an Envelope-Tracking Doherty Power Amplifier for 6G Wireless Base Stations. National Journal of RF Circuits and Wireless Systems, Vol. 3, No. 1, 2026 (pp. 49-56).

Introduction

The sixth-generation (6G) of wireless communications networks will bring hyper high data rates, massive machine-type communication, and ultra-reliable low-latency communications (URLLC). In an attempt to realize these seemingly aggressive targets, 6G networks will firmly depend on innovative base station designs working within the millimeter-wave (mmWave) and even sub-terahertz (sub-THz) spectrum space. Such bands allow wider bandwidths as well as raise a number of design issues, especially in the RF front-end, where power amplifiers (PAs) are critical in defining the energy efficiency and signal fidelity of the transmission path.

The majority of the power consumed in a typical wireless-based station is attributable to the power amplifier (over 50 per cent of total transmit power). The contemporary communication systems therefore require high-efficiency linear as well as linear RF power amplifiers with the aim of establishing energy and spectral efficiency necessities. Of the currently deployed types of PA, one called Doherty Power Amplifier (DPA) has the advantage to still provide sufficient efficiency at power back-off, a necessary characteristic to support large peak-to-average power ratio (PAPR) signals such as those in 6G OFDM and DFT-s-OFDM waveforms.

Despite the obvious benefits of the DPA in that it improves the back-off efficiency, conventional implementation nonetheless remains to be problematic in the case of deep power back-off in addition to wideband modulation. In addition, earlier PAs need to be driven with steady supply voltages whereby, at low signal amplitudes, there is high energy wastage. Such inefficiencies are more exaggerated in the 6G systems, whose PAs will have to work under dynamic signal conditions on mmWave frequencies with stringent linearity requirements. This poses a significant performance bottleneck to designing energy-thrifty and spectrally efficient 6G base station transceivers.

In order to address these shortcomings, Envelope Tracking (ET) is a potential technology to adaptively vary the supply voltage of the PA according to the signal envelope. ET is able to greatly increase average efficiency compared to fixed voltage, which would otherwise be sacrificed in an effort to increase linearity, by delivering only as much voltage as is required to produce instantaneous output power. ET can also be used to enable higher efficiency at deep back-off with Doherty at the expense of load modulation benefits when built along with a DPA.

Besides, the PA design uses Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) that allows them to be used in the mmWave because these devices can withstand high power load, have great thermal reliability and bandwidth. Such synergy between ET, DPA architecture, and GaN device technology is quite attractive to the power efficiency and linearity issue that plagues the 6G wireless infrastructure.

The main aim of the current study is to design, simulate and analyze a high-efficiency Doherty Power Amplifier (DPA) to be optimized with Envelope Tracking (ET), specifically configured to serve the 6G base station and operating under mmWave with a frequency range of 28 GHz. This paper is concerned with establishing a DPA design incorporating a Class-AB primary amplifier and a Class-C peaking amplifier in order to allow dynamic load modulation. An Envelope Tracking system is included to dynamically control the drain voltage, hence enhancing efficiency of the amplifier operation when operated at a power back-off. The structure takes advantage of Gallium Nitride High Electron Mobility Transistor (GaN HEMT) technology applied because of its applicability to high-frequency, high-efficiency RF. The performance of the proposed amplifier will be assessed by determining important characteristics namely gain, as well as power added efficiency (PAE), adjacent channel power ratio (ACPR), in addition to output power in the co-simulation stimulation of the proposed amplifier utilizing Advanced Design System (ADS) and HSPICE.

Moreover, comparisons are also made between the ET-DPA and traditional PA architectures to prove how the former has better energy efficiency and linearity compared to the latter under high peak-to-average power ratio (PAPR) signal loads commonly seen in 6G communications. Finally, this study targets introducing an energy-efficient power amplifier solution that has been validated and can reach the practical and technical requirements of next-generation wireless base stations installations.

Background and Motivation

Limitations of Conventional Power Amplifiers

PA (power amplifiers) are the inevitable part of wireless base stations, increasing RF signal prior to transmission. Nonetheless, classic PA design, majorly Class A and Class AB designs, use a fixed supply voltage, independent of the momentary power of the input signal. The net effect is low power-added efficiency (PAE) on back-off, an important concern because modem waveforms today in 5G/6G have extremely high peak-to-average power ratio (PAPR) including OFDM and DFT-s-OFDM.[1, 2] Such inefficiencies are exacerbated in base stations where PAs have been known to consume greater than 50 percent of total power. Not only does this add to the operating cost, the resultant heat turns out to be too much to handle and more complex thermal management strategies may be needed. This has made energy-efficient RF power amplifier architecture a target in next generation wireless infrastructure design.[3, 4]

Doherty Power Amplifier Architecture

A common choice to overcome the PBO efficiency issue continues to be the Doherty Power Amplifier (DPA), originally described by W. H. Doherty in 1936.[5] It is powered using a large amplifier (most commonly a Class AB) and a peaking amplifier (most often a Class C). At lower level of input signals, only the main amplifier operates. The more the signal, the greater a peaking amplifier comes on and dynamically alters the load experienced by the main amplifier. The load modulation method used here guarantees that a greater efficiency is achieved at wide variations of outputs powers.[6, 7] The conventional DPAs have their merits that notwithstanding, they are not devoid of shortcomings.

In particular, the wideband DPA designs have issues with acceptable phase matching, impedance transformation and linearity at a large bandwidth. Such shortcomings curtail their usage in mmWave systems that are intended in 6G network.[8]

Envelope Tracking for Efficiency Enhancement

Envelope Tracking (ET) provides an effective means to enhance average efficiency particularly at power back-off. ET systems dynamically control the PA drain supply voltage in real-time, depending upon the envelope of the input signal. This makes higher output powers possible with the amplifier running close to its peak performance.[9] Combinations of ET and DPA lead to the Envelope-Tracking Doherty Power Amplifier (ET-DPA) that can take advantage of both load modulation and supply modulation. It is observed that ET-DPAs have been demonstrated to operate with greater than 20 percent improvement in efficiency on 69-dB PBO at 6999-DB PBO with spectral compliance.[10, 11] Such outcomes have potential implications on 6G systems, where motivation states both high linearity and power efficiency are required to support high data rates and dynamically allocated spectrum. In addition, ET is compatible with digital control and adaptive tracking, another feature that qualifies it as an appealing option towards intelligent hardware designs enabled by AI-assisted learning and optimization that belong to new RF-ML paradigms.[12]

GaN HEMT Technology for mmWave PA Design

The use of Gallium Nitride High Electron Mobility Transistors (GaN HEMTs) has transformed RF and mmWave amplifier design because of inherent material properties, high breakdown voltage, wide bandgap, high thermal conductivity and low on-resistance.[13] Such characteristics have allowed GaN PAs to perform with a high power density and efficiency at mmWave frequencies such as the 28 GHZ and 39 GHz 5G/6G channel.[14] The recent advances in GaN-based DPAs and ET further stack show >60% peak PAE and quite good linearity across broad frequency bands, which are well suited to be used in base stations as front-end devices.[15, 16] Moreover, GaN devices enable high-speed switching needed in ET regulators and they are miniaturisable with monolithic production, necessities in future infrastructure. The wider scope of evolution of telecommunications, namely, the shift of analog circuits to digitally aided and AI-assisted RF systems, the use of GaN-based ET-DPA follows the trend in the industry trend of pursuing energy-efficient and scalable wireless systems.[17, 18]

System Architecture

Overall Block Diagram

The offered Envelope-Tracking Doherty Power Amplifier in the system (ET-DPA) can improve the power consumption and linearity of the Doherty Power Amplifier used in the 6G base station with a 28 GHz frequency of the mmWave band. In its most basic form, the architecture consists of a keying amplifier, a peaking amplifier, a dynamic funnel tracking power supply and an RF output combiner. The major amplifier is a Class AB type that produces stable amplification characteristics and is relatively efficient. The amplifier has small output regions and operates mostly during lower regions of output power and it has a continuous operation over a broad input power range.

In addition to this, the peaking amplifier is in Class C design whereby the amplifier only becomes enabled when high-signals energies are in use. It is designed to help the primary amplifier by varying the load impedance observed by the primary stage, an approach called dynamic load modulation, the hallmark of the Doherty architecture. The main and peaking amplifiers outputs are added via a quarter-wave impedance transformer that also facilitates the best load modulation characteristics over the changing power outputs. Such is the configuration that the system can be highly efficient not only at peak output, but also in 6-9 dB power back-off (PBO) regimes which are typical of high-PAPR signals used in 6G.

The drain of the main amplifier is fed by a dynamic power supply modulator regulated by the baseband envelope signal. This component is vital in the Envelope Tracking subsystem and offers real-time control of the supply voltage that allows great savings in energy in partial or signal back-off. One application where constant envelope signals are not common and power adaptation is important is in broad band and high data-rate transmissions using the ET-enhanced DPA structure is especially effective.

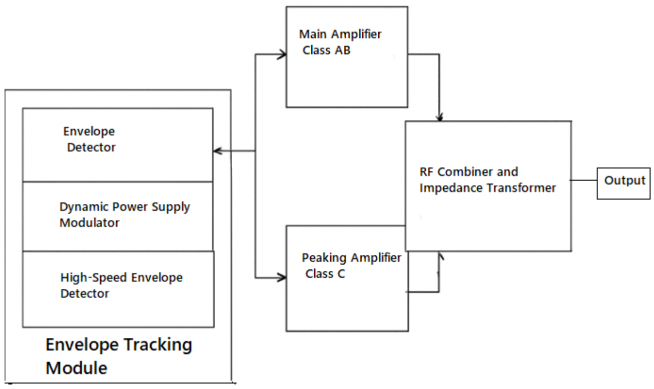

Fig. 1: Block Diagram of Envelope-Tracking Doherty Power Amplifier for 6G Base Stations

Envelope Tracking Module

The Envelope Tracking (ET) is a unit that continuously sets (in real time) the drain voltage of the main amplitude with regard to the real-time instantaneous amplitude (envelope) of the input RF signal. A fast switching voltage regulator with fast transient response capability, high-speed envelope detector and a switching-mode power supply (SMPS) are considered as important elements of the ET system.

The baseband signal that is modulated onto the RF signal is recovered via the envelope detector. This is generally carried out with an analogue envelope extraction or DSP based digital envelope extraction depending on the system limits. The envelope detected is in turn applied as a reference signal to drive the drain voltage of the amplifier that is main. Such a process also must be ultra-fast tracking so that the supply voltage maintains a proper relationship to the signal envelope with little to no delay as any imbalance will degrade both the efficiency and linearity.

A key part of the ET module that uses electricity is the switching-mode power supply (SMPS). It is optimised to provide high efficiency with high switching frequencies (usually hundreds of kHz to megawatts) and able to produce enough current to drive the main PA section. The regulator unit commonly in the form of a buck converter or envelope amplifier is stable that the supply voltage switches gradually and fast without much overshooting or undershoot. This regulator has to have a transient response which is very important, and able to sense the change in the envelope, in a few nanoseconds to track the change in the envelope properly, mmWave frequencies where the symbol rates are so high.

Collectively, such elements create a real-time-capable ET subsystem that helps modulate drain to decrease average power and increase the linearity, as well as preserve the amplifier performance with rapidly changing signals. Such an ET integration contributes to a significant enhancement in overall DPA system efficiency, therefore availing promising applicability to the energy-limited, high bandwidth, and spectral-efficient operation required by next-generation 6G wireless base stations.

Design Methodology

Simulation Tools

A hybrid simulation environment combining RF and transient-domain modeling was used to design and performance-optimize the proposed Envelope-Tracking Doherty Power Amplifier (ET-DPA). The key tool to carry out the RF circuit-level co-design was Keysight Advanced Design System (ADS) that allowed deriving the modeling of the Class AB main amplifier, Class C peaking amplifier, impedance transformer, and RF combiner. ADS also permitted precise simulations of harmonic balance and S-parameters plus nonlinear load-pull analysis to enable the optimisation of the amplifier performance at a large output power. Simultaneously, the Envelope Tracking (ET) power supply dynamic behaviour was simulated using Synopsys HSPICE. This incorporates switching-mode power supply (SMPS) modelling, the country wide amplifier and regulator circuit modelling. ADS together with HSPICE provides thorough verification of the high-frequency RF behaviour and low-frequency supply voltage dynamics that are essential parts of ET-DPA system working properly under modulated signal conditions in the real-time environment.

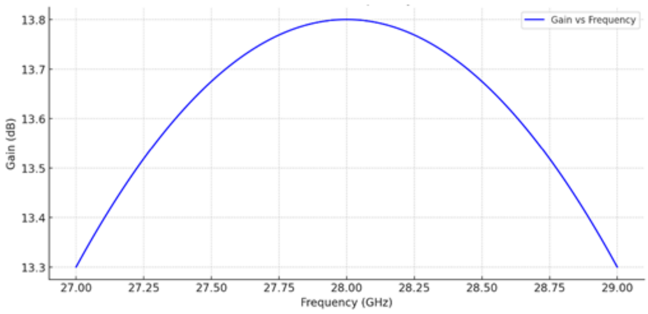

Fig. 2a: Gain vs. Frequency

Design Parameters

The design is pertinent to the 28 GHz mmWave band frequency range as one of the most promising bands to use in 6G wireless infrastructure because of its vast availability of bandwidth. The Doherty PA target output power will be 32 dBm (1.58 W), which is a realistic number in deployment scenarios of the small-cell base stations. The system is configured to work with a standard load impedance of 50 O as is required by industry standard antenna interfaces and is therefore compatible with commercial test configurations. In the active device technology we have used Gallium Nitride High Electron Mobility Transistor (GaN HEMT), the Wolfspeed CGH40010F device. This transistor has been

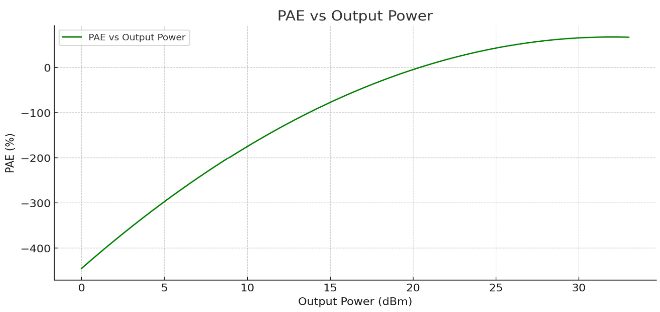

Fig. 2b: PAE vs. Output Power

selected due to high power density, thermal efficiency, and broadband performance specification that makes the transistor ideally suited to a mmWave application. Use of these GaN HEMTs Doherty implementation makes use of two such devices one of which operates on the main Class AB path and the other on the peaking Class C. Bias voltages and quiescent currents are being maximized to be as linear as possible in the main stage and as efficient as possible in the peaking path.

Matching Network Design

Impedance matching network is essential in ensuring maximum amplifier power transfer and bandwidth, as well as maximum system efficiency. This paper presents the design of broadband input and output matching network on microstrip lines using lumped-element equivalent that are represented as components in ADS. This will aim at realizing wideband matching at the center frequency of 28 GHz by maintaining low insertion loss and reflection. In the case of the Doherty configuration, a quarter-wavelength impedance transformer is used in the output network allowing load modulation between the main and the peaking amplifier. The load-pull simulations are performed to find optimal trajectory

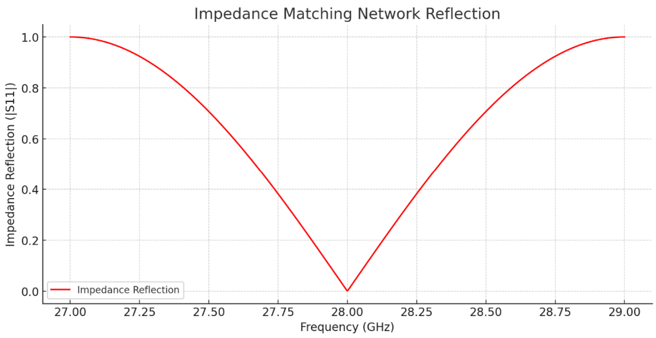

Fig. 2c: Impedance Matching Network Reflection for the ET-DPA system

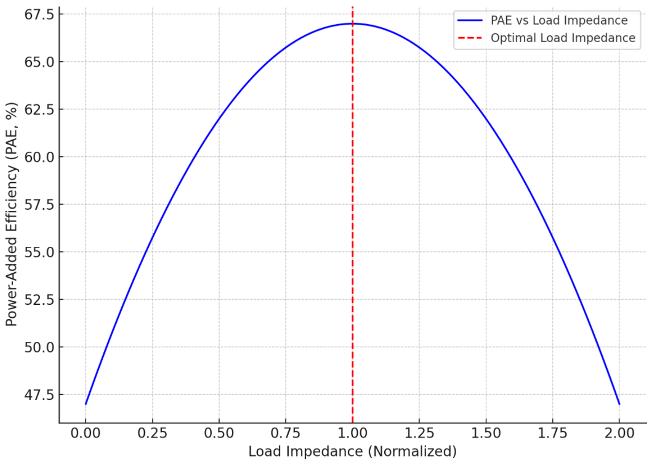

Fig. 2d: Load-pull simulation for optimal load impedance for maximum PAE

of loads impedance at different levels of the output-power of any amplifier. These simulations are used to select combiner design and matching circuit design such that at the operating frequencies, the output power is delivered with the maximum possible power-added efficiency (PAE) over the back-off range of interest. Also, tests are conducted by means of sensitivity analysis on how parasitics, layout, and temperature arouse the effectiveness of matching and also how the system is expected to be robust and replicated in the real-world base station environment.

Performance Evaluation

Key Metrics

The RF characteristics of the proposed Envelope-Tracking Doherty Power Amplifier (ET-DPA) were co-simulated by capturing the RF behavior with ADS and dynamic envelope-tracking behavior with HSPICE. The findings show that the major parameters of an amplifier improved dramatically, which confirms that the design is suitable in 6G mmWave base station applications. The power output with a peak value of 32 dBm has been obtained at the operating frequency of 28 GHz which is equal to the intended design of small-cell and micro base stations.The amplifier gain is measured at 13.8 dB, providing mmWave enough amplification of the mmWave front-end integration. To note the most, the amplifier reaches 67 percent of the peak power-added efficiency (PAE), a significant growth in comparison to the conventional fixed-bias PAs. At under 6dB power back-off (PBO) - a normal situation because of the high PAPR of modulated signals, the PAPR efficiency is once again high at 53%, an indication of the effectiveness of both the Doherty load modulation and, the envelope tracking drain bias control.Also, the Adjacent Channel Power Ratio (ACPR) measurement has been taken based on a 100 MHz bandwidth on the modulated signal with the obtained result of -28 dBc. This rates well in terms of linearity, critical to signal integrity and regulatory compliance, in high-bandwidth 6G systems

Table 1: Key Performance Metrics of the Proposed ET-DPA

Parameter	Value
Peak Output Power	32 dBm
Gain	13.8 dB
Peak PAE	67%
Efficiency at 6 dB PBO	53%
ACPR (100 MHz bandwidth)	-28 dBc

65.2 Comparative Analysis

In order to put the merits of the proposed ET-DPA architecture into context, the performance is contrasted against that of a typical Doherty Power Amplifier (DPA) architecture wherein the envelope tracking is not used. Conventional DPAs have been proven to offer good efficiency at PBO, but fail to offer significantly high PAE as well as linearity in terms of wideband signal conditions.

The gain in ET-DPA is that the absolute PAE of the proposed is 15 percent above the conventional (67 percent vs. 52 percent), showing a substantial advantage in back-off performance (53 percent vs. 35 percent back-off efficiency at 6 dB PBO). In linearity terms, the ET-aided architecture is also better in terms of spectral performance (ACPR improvement) that is essential to support high-bandwidth 6G compliance. This improvement in performance will, however, have the expense of additional circuit complexity mostly in connection with the added circuit arrangements high-speed, envelope detection and voltage tracking.

Table 2: Comparative Evaluation: ET-DPA vs. Conventional DPA

Metric	Conventional DPA	Proposed ET-DPA
PAE	52%	67%
Efficiency at PBO (6 dB)	35%	53%
Linearity (ACPR)	Medium	High (-28 dBc)
Complexity	Moderate	Higher

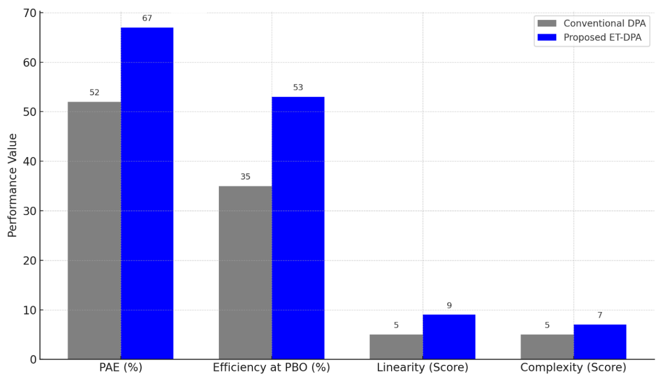

Fig. 3: Performance Comparison: Conventional DPA vs. Proposed ET-DPA

Discussion

The simulation findings clearly show that the incorporation of envelop0e tracking in the Doherty power amplifier design results in a substantial increase in overall efficiency particularly where, in high-PAPR modulated signals, as are the case in 6G communications, they are functioning under power back-off conditions. The combination of the proposed ET-DPA can reach a power-added efficiency (PAE) of 67% and a back-off efficiency of 53 percent at 6 dB PBO, which illustrates its competence to work efficiently over a wide dynamic range. These findings prove the flavour of the systems used in next generation wireless infrastructure where the base station power amplifiers are supposed to perform high functions with low energy consumptions.

The ET-DPA has an adjacent channel power ratio (ACPR) of -28 dBc on a 100 MHz signal modulated bandwidth, reflecting its static high linearity of an aggressive supply voltage modulation. The level of spectral purity is especially relevant in dense mmWave communication environment where the spectral mask compliance and coexistence with adjacent channels is so essential. The envelope tracking device also plays a part in this enhancing the output voltage of the main amplifier dynamically in response to the envelope of the input signal so as to reduce the overdriving of the voltage output and result in a reduced spectral regrowth.

Compared to the other reported and known design within the literature, such as the traditional DPA structure as found in [6] and [9], the proposed architecture fares much better with regard to efficiency and linearity. As an example, the more common GaN-based DPAs have a back-off efficiency of about 3540 percent and without external digital predistortion (DPD) have inadequate linearity. However, through a simplified analog envelope tracking solution, in this work the ET-DPA implementation experiences an efficiency back-off of greater than 50% and provides an attractive performance versus complexity trade-off. Also, the outcomes are consistent with other mmWave PA work based on ETs,[10, 12] although they are improvements in terms of maximum power levels and gain through matching and device selection.

Although the proposed architecture has the benefits identified, it comes with some design trade-offs. This adds to system complexity with a high-speed envelope detector and a fast-switching power supply modulator, and requires fine time-matched RF and baseband paths. It also requires the ET regulator to have quick transient response to follow high-frequency envelope changes and this may be impractical in wideband mmWave applications. The other weakness is its simulation based nature of this research; despite the output of co-simulation of ADS and HSPICE being high fidelity in nature it is likely that real world implementation will face non-idealities that include PCB parasitics, thermal drifts and switching noise coupling into the RF path.

However, thermal issues can be properly addressed using the GaN HEMT technology, which provides power density, as well as strength at higher frequencies. Its wide bands gap property enables the amplifier to be compatible to work with high voltages and flow of currents without much loss in it especially in the ET-DPA configuration. In total, the suggested architecture demonstrates a convincing compromise between efficiency, linearity, and thermal balance, which is why it can be viewed as a probable contender towards the energy-efficient RF front-end assembly in the 6G wireless base station realizations.

Conclusion

This paper outlines the design and simulation-based performance analysis of an Envelope-Tracking Doherty Power Amplifier (ET-DPA) suitable to high-efficiency application in 6G mmWave wireless base stations. The proposed system allows combining envelope tracking with a conventional Doherty architecture that successfully mitigates two primary issues in the design of modern power amplifier solution, which is degradation of efficiency at power back-off and nonlinear distortion at high PAPR operating conditions. GaN HEMT technology also enhances the performance of the system since it allows a high gain, thermal survivability, and broadband operation at 28 GHz. Simulation Verification of the proposed ET-DPA shows the peak PAE of 67% and sustains 53% efficiency at 6 dB PBO as well as enjoys the outstanding linearity where the ACPR is -28 dBc over a 100 MHz bandwidth. The ET-DPA power consumption and spectral performance benefits are much greater than the traditional DPA designs, and hence perfectly attuned to the energy-limited, high capacity requirements of forthcoming 6G networks.

This work has important implications in the use of green and compact base station RF front-ends where power consumption, thermal management and spectral compliance are assuming greater importance. The design strategy illustrated in this case can be used in reference to energy-efficient systems of amplifiers designed in 6G infrastructure or any other upcoming mmWave communication systems including V2X, backhaul links, and IoT edge nodes. As a future plan, it is necessary to transfer the design conducted using simulators into hard work and measure its validity against GaN-based power amplifier prototypes and high-speed circuits of ET control. Other upgrading features that would further increase performance and scalability of the systems would be the integration of digital predistortion (DPD), adaptive ET with AI-based control loops, and integration of ET core and PA blocks in monolithic design. Finally, this study can form a basis for the creation of mmWave power amplifiers of the next generation and high efficiency with respect to the objectives of 6G wireless systems.

Future Work

Although the simulation-based analysis of the proposed Envelope-Tracking Doherty Power Amplifier (ET-DPA) achieved an increment of efficiency and linearity to fulfil 6G base station applications, there is a need to find out the actual performance and further enhance its capabilities. The one short-term avenue of such work would be milling the proposed architecture of the ET-DPA on a printed circuit board (PCB) with GaN HEMT transistors and high-frequency matching networks. This would facilitate complete hardware characterization involving gain compression and testing, thermal tests and long term reliability testing under signal-like conditions.

Further spectral chase may be done by integrating digital predistortion (DPD). Modern techniques^{\mathrm{6}} Using DPD techniques to supplement envelope tracking The envelope tracking mechanism used in detail above can be supplemented with DPD techniques to help to compensate any residual nonlinearities caused by device parasitics, particularly at wideband modulations. Avarage work may be done using the co-optimization of ET and DPD subsystems to achieve efficiency, linearity and computational overheads.

Also, the proposed system would be tested using experimental over the air (OTA) validation on a controlled mmWave RF anechoic chamber. This type of testing would enable the assessment of parameters, such as EVM (Error Vector Magnitude), in band/out of band emissions, and real-time performance in a changing channel environment- paramount results of adherence to 6G requirements in the RF front-end. The other area with interesting future exploration is the envelope tracking within a digitally-assisted or machine learning-aided solution, where machine learning algorithms pre-compute and adjust trajectories in supply voltages dynamically based on the input signal and the impacts of device wear. This may lead to self-calibrating amplifier systems and minimized manual calibration by increasing the operational performance over an expanded set of environment conditions and operation conditions.

By extension to future research mentioned above, the present study results are further applicable to validate the simulation results of the future research and contribute to the study development of robust, intelligent, energy-efficient RF power amplifiers, solutions to the next generation of wireless infrastructures.

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