Enhancing Microwave/mm-Wave Power Amplifier Efficiency: A Key Solution to Global Energy Shortage Challenges

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1. Introduction

In human society, Energy is the backbone of modern civilization and is limited, which powers everything from homes and industries to transportation and communication systems. Because of this, Energy shortages are one of the most important problems facing human society. A shortage of energy leads to significant disruptions in daily life, economic activities, and overall societal functioning.

This energy shortage can cause concern in two ways:

1- Energy shortage in the real sense that leads to the need to produce more energy

2- Energy production from non-renewable sources leads to an increase in environmental pollutants.

Today, the second issue is the focus of attention for governments, particularly among European Union members.

Because of this, interest in renewable energy has grown [1] since the 1860s and 1870s, driven in part by the desire to reduce reliance on non-renewable sources and ensure that energy use and generation are sustainable [2].

In this case, improving energy efficiency can significantly help address global energy shortages by reducing the overall demand for energy, making the most of existing resources, and easing the strain on energy infrastructure.

The global challenge of energy efficiency revolves around the need to reduce energy consumption across all sectors while meeting the growing demands of a rapidly expanding population and economy. As the world faces the dual pressures of depleting natural resources and the environmental impact of energy production, improving energy efficiency has become crucial for sustainable development.

In general, energy efficiency involves using less energy to perform the same task or achieve the same level of service. This can be achieved through technological advancements, better infrastructure design, and changes in behaviour and policy. The challenge lies in implementing these measures across various sectors, including transportation, industry, buildings, and utilities, which are responsible for a significant portion of global energy consumption.

So, addressing this challenge is vital for reducing greenhouse gas emissions, mitigating climate change, and ensuring energy security. It also has economic benefits, such as lowering costs for consumers and businesses and reducing the need for investment in new energy infrastructure.

Telecommunications systems have been integrated into the fabric of modern society as a central part. They have transformed how we communicate, conduct business, access information, and entertain ourselves. Their impact is felt across economic, social, political, and cultural domains, making them a cornerstone of contemporary civilization and as we continue to advance technologically, the role of telecommunication in shaping our future will only grow. As mentioned earlier, reducing energy consumption has always been a major challenge for most systems, and wireless transmitters are no exception.

This heightened awareness of our impact on the local and global environment has put pressure on the communications industry to reduce power consumption by improving the efficiency of the communication chain.

The reality, however, is that the communications industry still has a long way to go. Nonetheless, additional pressures beyond environmental concerns are driving this change. Inefficient products harm the environment lead to short battery life in handheld devices and significantly increase operating costs for base stations due to higher energy consumption and additional cooling requirements. So, the efficiency improvement of these systems has long been a hot topic in electronic circuitry research in both academia and industry. In this work, we aim to provide valuable insights into enhancing the efficiency of modern communication systems by focusing on power amplifiers, the most critical component in terms of energy consumption in the whole chain of modern communication systems.

2. 5G networks as the most popular global wireless systems

The mobile communication revolution began in the early 1980s with the introduction of the first Motorola DynaTAC mobile phone. At that time, communication was analog, and the mobile phone was used solely for making calls. This was the first generation of mobile networks, known as 1G, which paved the way for the future of telecommunications. In the following decades, new uses and subsequent generations of mobile networks emerged. With 2G, using various standards such as GSM, GPRS, and EDGE, the era of text messaging began, along with the introduction of early mobile "Internet" connectivity. With the advent of 3G in the 2000s, the UMTS, HSPA, and CDMA2000 standards enabled multimedia usage. This generation made it possible to browse the web, send emails, stream music, and share videos, thanks to significantly higher data rates compared to the previous generation. The first smartphones began to appear, diversifying usage patterns. However, data rates in 3G were relatively low. This exponential increase in multimedia usage created a demand for higher data rates.

Smartphones have become an integral part of our lives, leading to continuous growth in the mobile market since their introduction. In their mobility report, Ericsson [3] analysts project future market trends related to broadband mobile subscriptions. In their mobility report, Ericsson analysts project significant growth in broadband mobile subscriptions. They anticipate a more than 230% increase in 5G subscriptions by 2029 compared to 2024, rising from 1.7 billion users in the first quarter of 2024 to 5.6 billion in 2029. This growth, driven by the rising adoption of smartphones in Asian countries, is expected to add nearly 3.9 billion 5G subscriptions, contributing to a total of 9.3 billion mobile subscriptions across all generations (5G/4G/3G) worldwide, as illustrated graphically in Fig. 1.

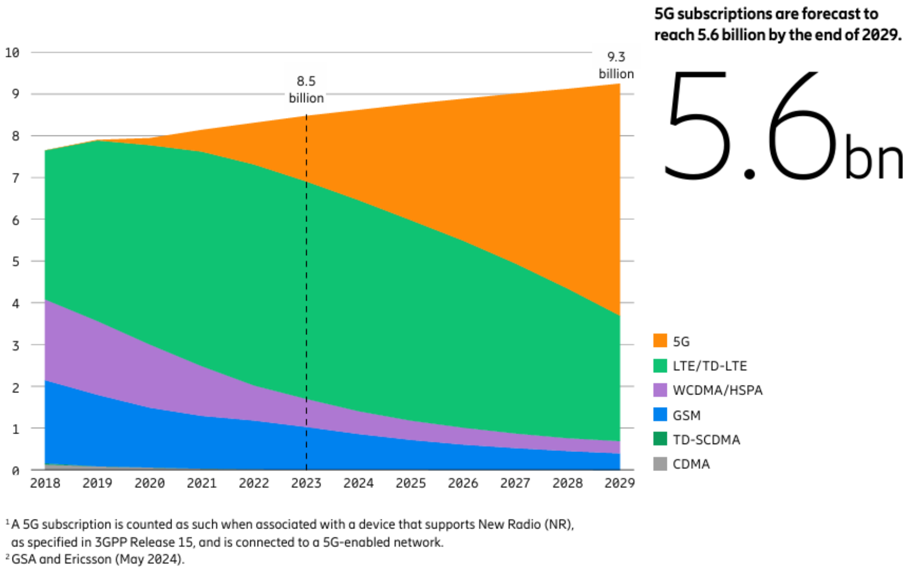

Fig. 1. Mobile subscriptions by technology (billion) [3]

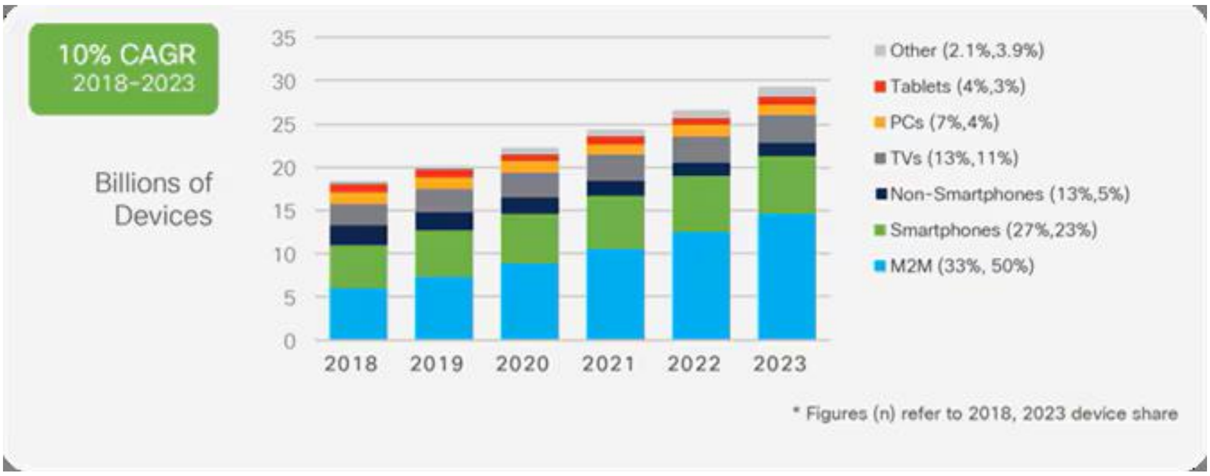

Fig. 2. Global device and connection growth [4]

Meanwhile, analysts from Cisco [4], are expecting more than 5.3 billion total internet users in 2023 increasing more than 35% compared to 3.9 billion users in 2018. In addition, this report has mentioned, that the number of devices connected to IP networks will be more than three times the global population by 2023 compared to 2018. There will be 3.6 networked devices per capita by 2023, up from 2.4 networked devices per capita in 2018. There will be 29.3 billion networked devices by 2023, up from 18.4 billion in 2018, which has been showed in Fig.2. The 5G infrastructure Public and Private Partnership [5GPPP] expects the emergence of the connected world to "connect over 10 trillion wireless devices serving over 10 billion people". In addition, a significant revolution in usage is anticipated in the future connected world. Everything and everyone will be connected, anywhere and anytime. Transportation will become smarter and safer with the advent of autonomous vehicles and the monitoring, optimization, and security of transportation networks. Cities will also become smarter and safer. The flow of resources will be monitored and managed through IoT (Internet of Things), exemplified by constant and automated quality checks of drinking water. Homes will also become connected, enhancing safety, improving resource management, and offering greater convenience through home automation.

The emergence of these new applications necessitates a rethinking of mobile networks, which are currently centered around smartphone usage. A new network architecture, interoperable with existing networks, is required to enable this connected world. As Nokia stated, "Driven by the enormous increase in mobile data traffic and flourishing user demands, we need to look beyond 4G." It was in this framework that 5G, the next generation of mobile networks, emerged in 2020.

With the significant increase in data usage anticipated for 5G, higher data rates of around 10 Gbps downlink speed are expected. This will enable ultra-HD video streaming and provide instant access to any content, making the internet more interactive [5].

3. Efficient Energy telecommunication systems

The rapid growth in voice and data transmission usage and advancements in energy-saving technologies are the two dominant and increasingly undeniable trends shaping the global communications landscape.

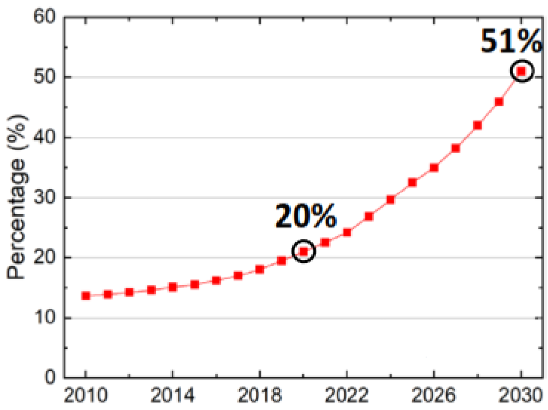

Fig. 3. Share of Wireless Network in Global Electricity Usage [7]

This increase in data transmission usage, from 1G to 5G or beyond, creates difficult requirements for the adopted signals in modern communication systems and imposes stringent requirements on these signals, which leads to an increase in the power consumption of the telecommunications hardware especially in the Base stations. So, as we advance toward new generations of wireless communication, including 5G, the share of wireless networks in global electricity usage is increasing, as shown in Fig. 3[7]. The reasons behind this issue will be discussed further.

In any telecommunication system, there are many building blocks, such as power amplifiers, active cooling systems, and DC-DC power supplies, whose contribution to energy consumption varies depending on the nature of their operation. As illustrated in Fig. 4, which shows the power distribution in a 4G base station [8], the power amplifier (PA) is the most power-consuming component, accounting for 57% of the total power consumption, surpassing all other components.

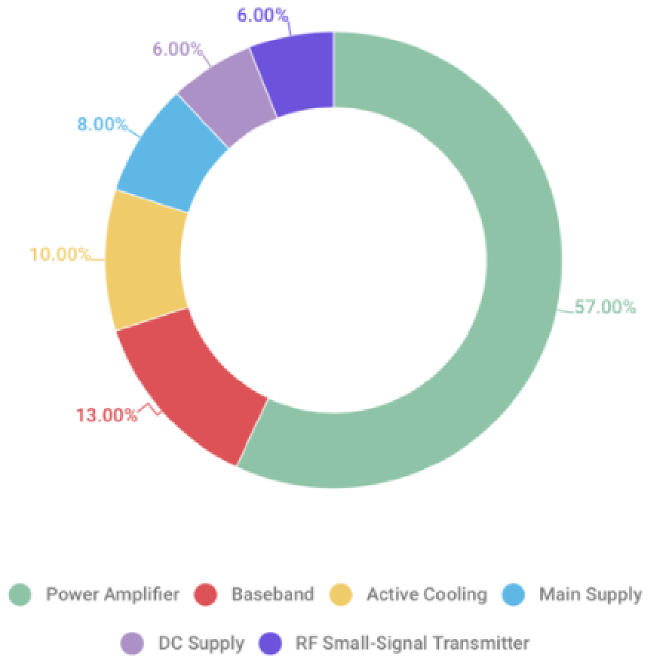

Fig. 4. Consumption power distribution in 4G base station (data from [8])

4. Efficiency Challenges of Power Amplifiers in the Era of 5G Signals

Since the power amplifier is the primary source of energy consumption in the entire base station chain, its efficiency greatly impacts the overall efficiency of the telecommunications system. A deeper examination of the building blocks that contribute to power consumption in the entire chain of communication systems reveals that the efficiency of a power amplifier affects not only the power consumption of the PA itself, but also influences the energy consumption of the cooling system. As shown in Fig. 4., this cooling system accounts for nearly 10% of the total energy consumption of the entire system.

Low-efficiency amplifiers generate more heat because a greater portion of the energy is dissipated as heat rather than being converted into output power. In contrast, high-efficiency power amplifiers produce less heat, meaning the cooling system does not have to work as hard to remove excess heat from the amplifier and surrounding components.

The use of highly efficient power amplifiers can lead to more effective cooling solutions, including lower energy consumption for cooling, reduced cooling system size, and increased equipment longevity**. In summary, high-efficiency power amplifiers lessen the need for robust and costly cooling systems, resulting in savings in equipment costs, energy usage, and maintenance.**

Anyway, PA efficiency declines as we move toward newer generations of wireless communication systems, including 5G and beyond, as illustrated in Fig. 5.

Therefore, if we can find a way to improve the efficiency of the PA, we can more effectively enhance the overall efficiency of the entire system compared to other components.

But, why does the efficiency of PAs decline as we advance to newer generations of wireless communication systems? And what can be done to improve PA efficiency for these applications?

Several factors significantly contribute to the low efficiency of PAs in the new generation of wireless communication systems. Before addressing these factors, it is important to understand a concept related to the nature of the high data-rate signals used in the latest generation of wireless communication.

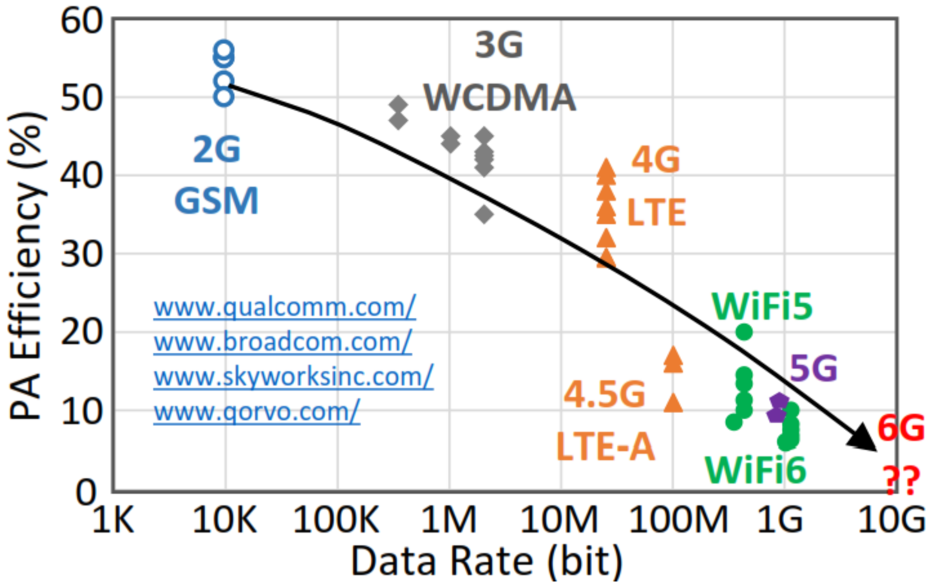

Fig. 5. Typical PA Efficiency for the different generations of wireless communication systems [9]

PAPR, which stands for Peak to Average Power Ratio, increases with higher data-rate signals. This is because higher data rates are achieved using more complex modulations, such as QAM and OFDM, to enhance bandwidth efficiency. However, the combined use of these modulations increases PAPR, as shown in Fig. 6.

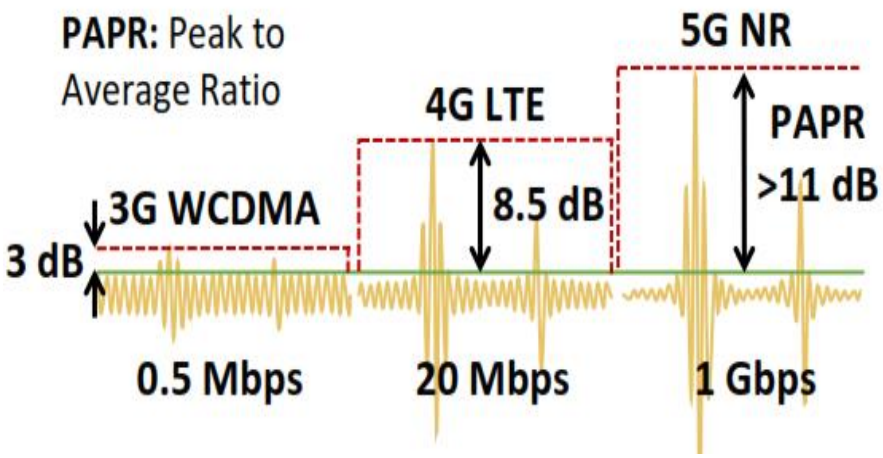

Fig. 6. PAPR Levels in the various generations of the wireless communication system [9]

The increase in PAPR leads to stricter linearity requirements. To prevent the PA from entering compression and causing distortion, it must operate within the linear region. High PAPR necessitates that the PA primarily operates at the average output power level, with significant back-off from peak power. This requirement makes conventional PA architectures, such as Class B, Class F, and Class J, types of single-ended power amplifiers unable to have a good compromise between linearity and high efficiency in the large back-off, which is needed for modern wireless communications, and specifically, they suffer from the low efficiency in the back-off region. Thus, new PA architectures, such as Doherty, Outphasing, and Envelope Tracking [11-13] have been arising to improve the efficiency in these critical power levels without almost compromising the linearity compared to the single-ended PAs.

Between these advanced architectures, Envelope tracking is usually appropriate for the low PAPR signals, and also because the envelope signal is a high power signal that requires a switching converter as a voltage supply modulator to maintain high efficiency which will lead to a more complex design. Outphasing structure is excellent for improving linearity at high output powers but typically suffers from reduced linearity at low output power where two large signals are subtracted to achieve low output power The major drawback of the Outphasing is the bandwidth expansion that occurs when converting I/Q signals into an out-phased format. [14].

As such, the Doherty architecture appears to be a promising solution, offering a good balance between output power, linearity, efficiency, and gain and it’s a good solution to have both high efficiency and high power for high PAPR signals.

However, despite its popularity as the preferred architecture for implementing PAs in 5G communications, the Doherty configuration still faces challenges regarding system efficiency. As a result, the Doherty PA has become the workhorse in this field today. Its efficiency performance is illustrated in Fig. 7 [15].

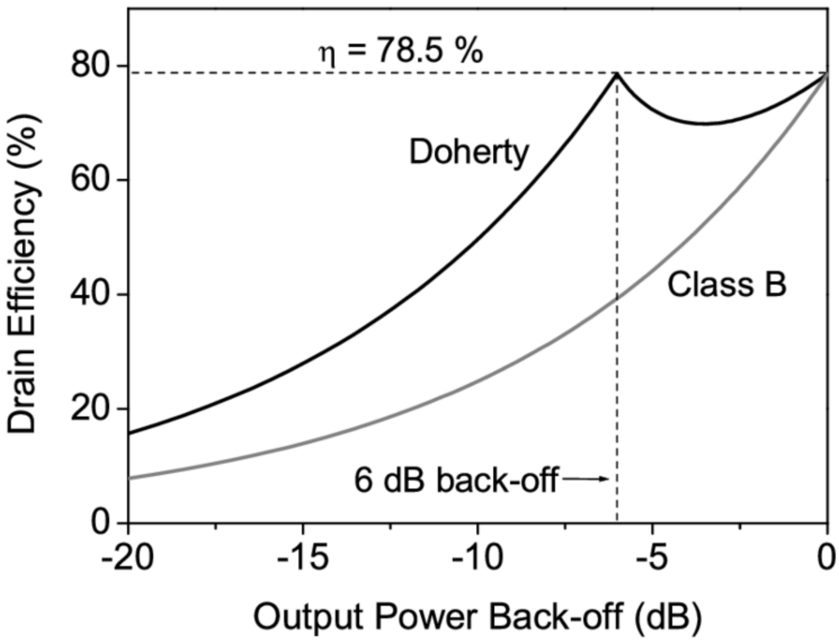

Fig. 7. Drain efficiencies of the ideal Doherty amplifier and ideal Class-B amplifier as a function of output power back-off [15]

The Doherty configuration consists of an input power splitter, two amplifiers—a main power amplifier biased near Class-B mode and a peak amplifier biased in Class-C mode—and an output combiner, which typically includes an impedance inverter and an impedance transformer to the load. Fig. 8. Shows the typical configuration of the Doherty Power Amplifier(DPA).

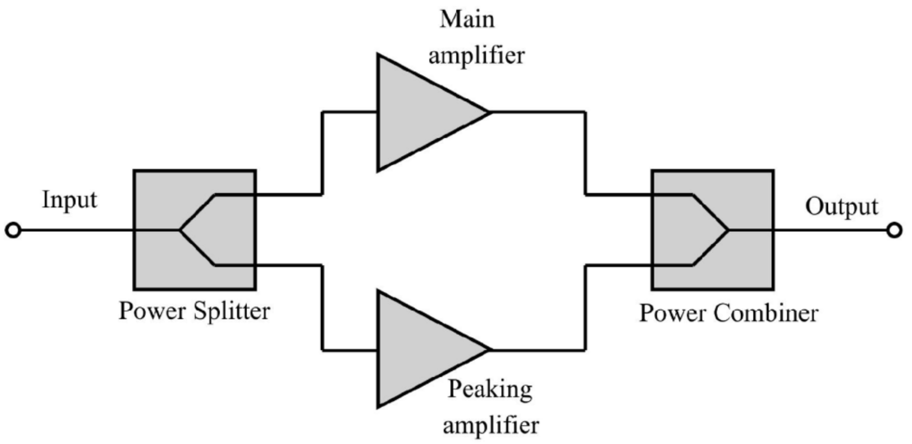

Fig. 8. Doherty power amplifier architecture

Three main factors contribute to the efficiency degradation of PAs used in the new generation of wireless communication, including 5G.

1- Higher frequency operation of the new generation of modern communication systems: Higher frequency operation is a defining characteristic of new-generation communication systems, particularly in the context of 5G and beyond, aimed at increasing bandwidth and supporting the high data rates required by these systems. These systems utilize millimeter-wave (mmWave) frequencies, which are significantly higher than those used in previous generations of mobile networks. However, the devices used to design PAs experience higher losses and lower efficiency at these frequency bands [10]. To solve this issue, the only solution is to develop significantly better active device technology with lower losses at high frequencies.

2- High level of efficiency degradation in the large Output back-off: The second drawback becomes evident by analyzing the efficiency behavior of DPA has OBO greater than 6dB, as shown in Fig. 9. The level of this efficiency degradation has been shown in Table. 1.

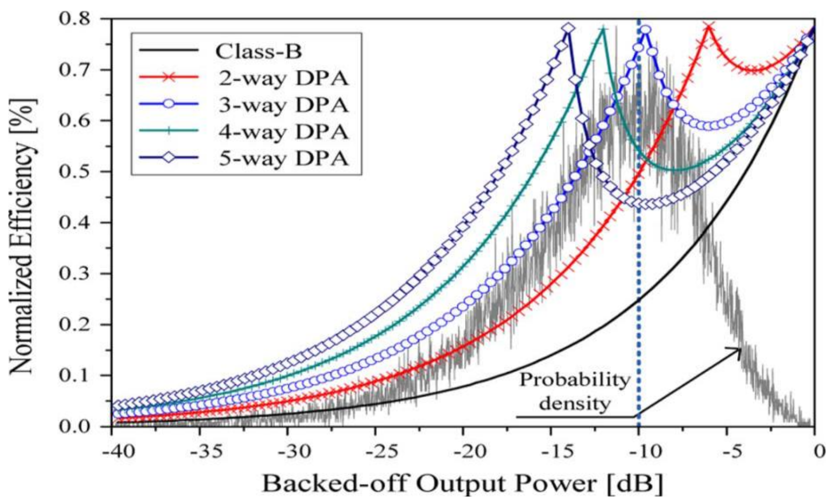

Fig. 9. Ideal efficiency of the N-way Doherty amplifier and probability density of a WCDMA signal [16]

Recently, we introduced a nonlinear power splitter tool that can control the phase between the two efficiency peak points. By adding different offset phases corresponding to varying signal amplitudes at the input of the Doherty configuration, this approach can effectively reduce efficiency degradation, offering a promising solution to this problem [17,18].

Table 1. Efficiency degradation level as a function of needed OBO (Output Back-Off)

OBO_needed	$\alpha = 10^{\frac{OBO_{needed}}{20}}$	$\Delta\eta = \eta_{max} \times \left(\frac{1-\alpha}{1+\alpha}\right)^2$ (Efficiency Degradation)
-6dB	0.5	$0.11\eta_{max}$
-8dB	0.4	$0.184\eta_{max}$
-9dB	0.355	$0.227\eta_{max}$
-10dB	0.316	$0.27\eta_{max}$
-12dB	0.25	$0.36\eta_{max}$

3- Transfer of the minimum efficiency point to deeper Output Back-Off (OBO): As shown in Fig. 9. when designing the Doherty power amplifier for higher output back-off (OBO) to accommodate high PAPR signals, the minimum efficiency point shifts to deeper levels of OBO, which is confirmed by the presented data in Table. 2. This is problematic as we move to newer generations of wireless communication systems. As illustrated in Fig. 10. with modern signal formats like LTE (which combines OFDM and QAM), the peak of the signal's PDF tends to occur at lower signal amplitudes.

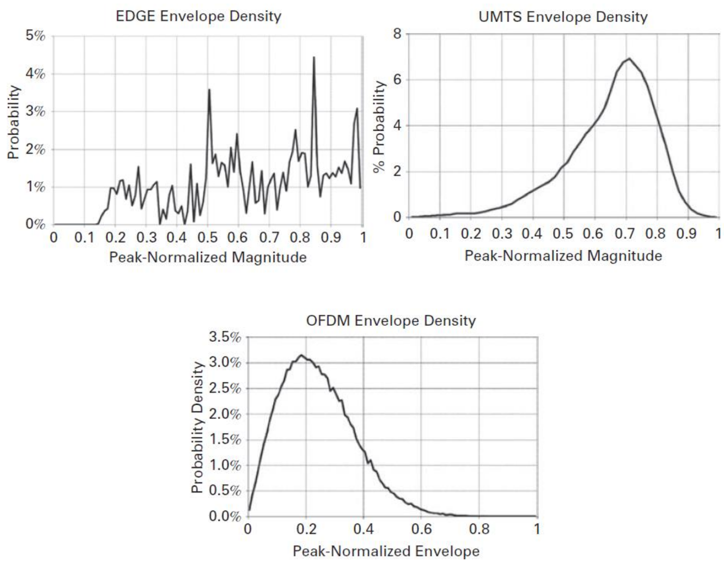

Fig. 10. PDF (Probability Distribution Function) of wireless signals [19]

Therefore, when combining the high OBO Doherty architecture with modern communication signals like 4G and 5G, which utilize OFDM and QAM formats, the average efficiency becomes significantly low, as illustrated in Fig. 5.

Table 2. Efficiency degradation point location as a function of needed OBO (Output Back-Off

OBO_needed	$\alpha = 10^{\frac{OBO_{needed}}{20}}$	$OBO_{min} = 20\log\left(\frac{2\alpha}{1+\alpha}\right)$
-6dB	0.5	-3.5dB
-8dB	0.4	-4.85dB
-9dB	0.355	-5.6dB
-10dB	0.316	-6.37dB
-12dB	0.25	-8dB

To address this problem, also in this case, the nonlinear power splitter can be used to shape the efficiency curve, shifting the minimum efficiency point to higher output power levels [18]. This adjustment is less critical for very high PAPR signals, such as those used in 4G and 5G systems. This solution is shown in Fig. 11.

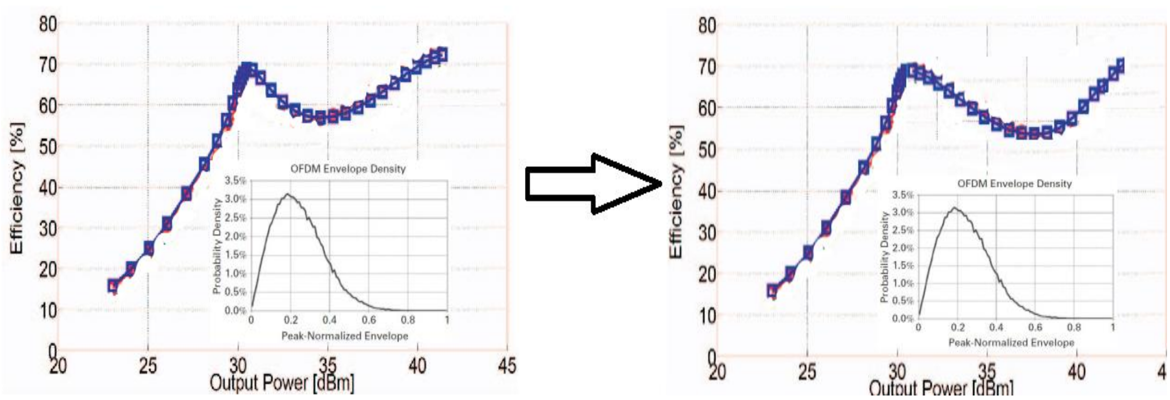

Fig. 11. Strategy to solve the third problem in DPAs

By addressing these issues and implementing potential solutions, we can overcome the efficiency challenges faced by power amplifiers in the new generation of wireless communication systems, including 5G and beyond.

5. Conclusion

In this work, we aim to demonstrate that, given the anticipated high demand for the next generation of wireless communication and the significant energy consumption of these networks in global electricity usage, it is crucial to find solutions to improve the efficiency of these systems. We also highlight that power amplifiers are the most critical element in the wireless communication chain, and improving their efficiency can lead to a significantly higher overall efficiency increase compared to other components. We then demonstrated that the Doherty power amplifier, widely regarded as the most popular choice for new generations of wireless communication such as 4G, 5G, and beyond, has fundamental issues that result in low average efficiency when dealing with these signals.

Finally, we addressed these issues and proposed some ideas that could potentially solve them. Addressing the issue of low efficiency in power amplifiers can lead to significant improvements in the energy efficiency of the entire communication system. This is due to enhanced energy efficiency in both the power amplifier itself and the cooling system. Increasing the average efficiency of power amplifiers by even 10% for the high demands of 5G wireless communication systems could significantly alleviate energy shortages, which remain one of the most pressing challenges facing our modern society.

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