PREFACE

Power Amplifier for 5G Technology : *Designs and Implementations* focus on the 5G technology, fundamental knowledge of power amplifier, 5G power amplifier design, design example of low-band 3.5 GHz power amplifier and high-band 28 GHz power amplifier. This book introduces 5G technology with Radio Frequency (RF) system architecture and frequency spectrum. The design challenging and device technology are also discussed. The background of power amplifier focuses on basic parameters, class E power amplifier, CMOS technology and substrate bias effect which put the reader in good pace to be able to understander more advanced in power amplifier design. In addition, this book highlights the specific 5G power amplifier design covers design procedure, specification, transistor size, load impedance, biasing and stability. Read this book to learn more about the design techniques for realizing power amplifiers for 5G application at low-band 3.5 GHz and high-band 28 GHz. The authors discuses design technique, layout and simulation results including comparison with existing state of the art power amplifier designs. This book is a comprehensive reference to student as well as practicing professional in academia and industry working in the area of Radio-Frequency Integrated Circuit (RFIC) design especially RF power amplifier. We sincerely hope you enjoy this book as much as we enjoyed putting it together.

Ahmad Fariz Hasan
Sohiful Anuar Zainol Murad

INTRODUCTION

This book has significant value to all level of students both undergraduates as well as, postgraduate students, researchers, and engineers in the field of Radio-Frequency Integrated Circuit (RFIC) design. This book provides comprehensive understanding state-of-the-art for RF design specifically Radio Frequency (RF) power amplifier design. It covers overview of 5G technology, fundamental of power amplifier, design implementation of 5G power amplifier, schematic design, layout and simulation results with an in-depth illustrative discussions and up-to-date references. It is useful as a reference and essential book for high-frequency circuit designers in both academia and industry.

The first chapter of this book covers introduction of 5G technology, RF system architecture for RF front-end design, 5G frequency spectrum in Malaysia and worldwide. It also presents the design challenging such as parasitic effect, transistor size, gate oxide and device technology. In the second chapter, it highlights the overview of power amplifier in general and basic parameters including gain, efficiency and linearity. In addition, basic theory of class E power amplifier followed by CMOS technology and substrate bias effect are discussed. Chapter three focus on addressing design procedure and specification of 5G power amplifier design. It also highlights the sizing of transistor, optimum load impedance, biasing and stability and finally reverse body bias technique.

The last two chapters details design example of power amplifier for 5G technology. In chapter four, a 3.5 GHz class E power amplifier is presented with design schematic and layout. Further, the simulation results are also discussed including comparison with existing state of the art power amplifier designs. Finally, chapter five focus on designing high-band 28 GHz power amplifier design. The cascaded amplification architecture is discussed with theoretical analysis. The authors also cover design implementation and layout with simulation results. Subsequently, the comparison with existing similar power amplifiers design is also included to validate the simulation results.

CHAPTER 1

INTRODUCTION TO 5G TECHNOLOGY

Telecommunication networks are introducing the new technological innovation called the Fifth-Generation (5G). This allows for cellular data rates of more than 10 Gbps for improved mobile broadband services, supporting 100 times more technological connected devices than the Fourth Technology (4G) to accommodate huge device communication, allowing the Internet of Things (IoT) and one millisecond latency for immediate behaviour with ultra-reliable device communications [1]. It would be incredibly difficult to meet the ambitious 5G targets all at once, so it is anticipated that the 5G transition would come roll out in phases [1], [2]. During the pre-standard 5G age in 2014, Ericsson 's live over-the-air demonstration network already reached a record of 5 Gbps capacity by utilizing a revolutionary modern radio interface design in conjunction with advanced Multiple-in Multiple-Output (MIMO) antenna technologies with shorter transmitting time intervals of 15 GHz and broader bandwidths [3].

In addition to the newly developed 5G wireless network framework and the planned for regional 5G architecture with a modern air interface, the Third Generation Partnership Product (3GPP) has announced its first research focusing on the New Radio (NR) for 5G, which aims to provide a wide range of device models, networks and implementations, and bandwidth at sub-6 GHz and mm-wave frequency [4]. The 5G NR covers all (fixed and mobile) broadband networking technologies at all frequencies [4].

This is particularly crucial in that with the million wireless devices needed for 5G, the power consumption of base station, wireless devices and the overall 5G infrastructure is reduced to a substantial reduction of about 90% of current 4G networks' energy demand efficiency [5]. Instead of using the sub 6 GHz wireless networks that have been done in the past for 2G, 3G and 4G, at least some of the 5G applications and networks would use larger spectrum ranges, smaller, huge MIMO phased array antennas for Three-Dimensional (3D) dimension beam forming at sub-6 GHz and higher mm-wave frequencies [1].

The output of Radio Frequency (RF) Power Amplifier (PA) will also control the transmitter (TX) results, since the Power-Added Efficiency (PAE) controls the heat dissipation and the power of the entire transmitter [6]. For an expanded user interface and large MIMO antennas in 5G, the 5G network would enable more PAs to be incorporated in the RF front-end modules, eventually making the design of the 5G PAs more complicated than the 4G PAs. The output power (Pout), cost, form factor and linearity of a PA are all critical elements for efficient commercialization of 5G applications [7]. Figure 1.1 shows an Integrated Circuit (IC) of 5G Front-End Module (FEM) configuration for MIMO phased-array antennas in mm-Wave.

As can be seen in Figure 1.1, the 5G PA, phase shifter, transceiver (T/R) switches, Low-Noise Amplifier (LNA) and other passives elements are all built into the FEM IC, in which the design is quite diverse from their 2G, 3G, and 4G equivalents and thus, has far more sophistication in the integration of IC [7]. In certain cases, the MIMO antennas may be mounted directly over the FEM IC wafer to attain better alignment with reasonable efficiency [7], [8]. Massive antenna systems and FEM ICs prefer silicone-based technologies for 5G mobile applications with a high integration requirement, although Gallium Arsenide (GaAs) and Gallium Nitride (GaN) FEMs generally have excellent performance as compared with silicone [8]–[10]. Besides the needs for convergence, as the Tx operating frequency rises to mm-Wave wavelengths, the design of a high-efficiency PA to solve the heating problem for efficient major MIMO realization is well-recognized as a very difficult challenge [11].

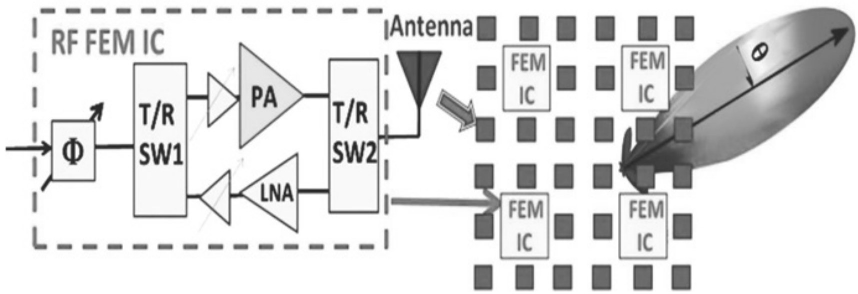

Figure 1.1. An example of a fully integrated Radio Frequency Front-End Module (RF FEM) with MIMO antenna [7].

1.1 RF SYSTEM ARCHITECTURE

The typical configuration of a personal communications RF transmitter and receiver (transceiver) network is shown in Figure 1.2, representing the system's transmitter and receiver sides, respectively. On the transmission side, data bits from the processor are converted to an analog signal using a Digital-to-Analog Converter (DAC) and this signal is then transferred to a higher frequency using a mixer. The explanation for adjusting the signal is because the frequency of communication is much higher than the frequency of data transmission. An amplifier now amplifies the resulting signal and an antenna broadcasts the message. Power amplifiers are used right before the antenna as the power of the signal must be increased to extend the distances to compensate for the attenuation. At the receiver side, the antenna will filter the signal to select the frequency range of interest. The Low-Noise Amplifier (LNA) will then amplifies the signal. The amplifier is not only designed to amplify the magnitude of RF signal but more significantly, it expands with the least amount of noise applied to the device.

Subsequent to the LNA, the signal is then sent to the mixer to transfer it to a lower frequency. This signal is converted into a digital signal with the use of an ADC. The final digital signal can be used for any processing needs by the on-board processor.

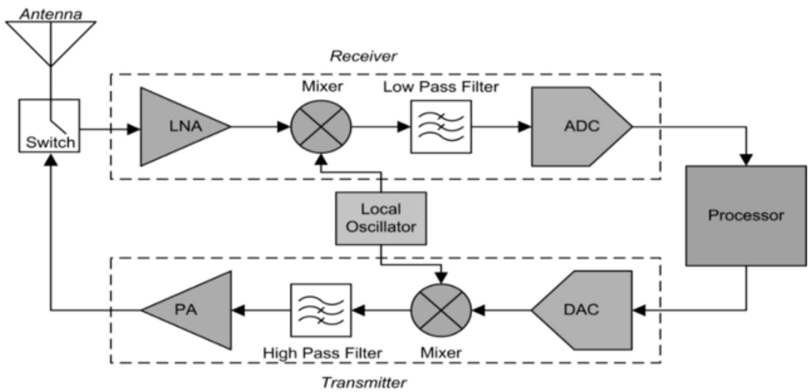

Figure 1.2. Basic of RF Transiever System [12].

1.2 5G FREQUENCY SPECTRUM

Like every wireless communication device, 5G mobile communication networks require the use of frequency spectrum to transmit data. The 5G needs a higher range of sub- 6 GHz and millimetre waves (mm-waves) to allow a higher bandwidth. Conventional Global System for Mobile (GSM) and Long-Term Evolution (LTE) networks use frequency ranges below 4 GHz, which causes bandwidth constraint. Enhanced mobile broadband experiences require substantial increase in bandwidth. There are also unused frequencies atlow frequency range, such as at mm-waves, for effective use of a higher bandwidth. In November 2018, a national 5G working group was formed to research and propose a holistic 5G strategy deployment in Malaysia. The 5G task force consist of private sector organizations, ministries and agencies representing the ecosystem's demand and supply side. Two frequency bands have been listed by the 5G task force as the priority spectrum for 5G rollout in Malaysia:

i) Frequency varies from 3.3 GHz to 3.8 GHz;
ii) Frequency varies from 24.5 GHz to 29.5 GHz

The above frequency ranges were selected based on global patterns and the complexity of the habitats. Figure 1.3 displays the worldwide range for 5G. Those bands were reserved or planned for potential 5G testing. Various countries have suggested and are operating on various frequency bands that range from 600 MHz to 71 GHz, depending on the frequency spectrum allocations.

The sub-6 GHz spectrum (3.3 GHz-3.8 GHz) and mm-wave spectrum (26 GHz-60 GHz) are becoming the next-generation carrier source due to the increase in data growth in cellular networks and these spectrum ranges are of interest for future 5G cellular networks [1]. The regional shortage of bandwidth faced by the wireless providers have prompted exploration of these underused frequency spectrums for future cellular broadband communication networks. However, the high-efficiency silicon Power Amplifier (PA) is still a challenge due to the entrance equilibrium between speed in silicon and the break-down voltage [13]. Power amplifier is an important component of the Radio Frequency Integrated Circuit (RFIC) design to convert from low-power to a higher-power signal in order to ensure that the RF system can deliver multimedia applications, high-quality low-latency video to a wireless device.

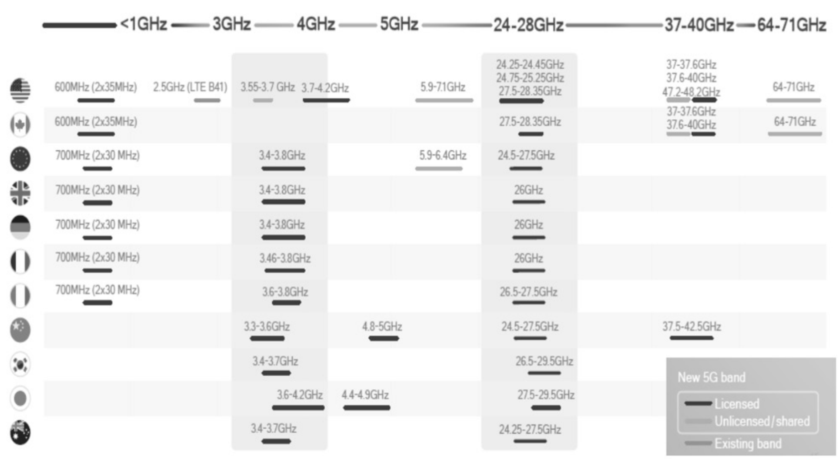

Figure 1.3. The 5G spectrum across the globe [14].

1.3 DESIGN CHALLENGE

With the rise of mobile data and the use of smartphones, the situation has create a peculiar contest for network providers to overcome a global shortage in bandwidth [1]. Therefore, the 5G frequency spectrum need to be explored to overcome this issue at sub – GHz and mm-wave frequency spectrum. Besides that many researchers have experience multiple challenges in implementing 5G power amplifiers such as the existence of parasitic capacitance from the transistor node which significantly degrades the Power Added Efficiency (PAE) at frequencies of interest in 5G [2]. Therefore, a proper design is needed to improve the PA's PAE for 5G application. Transistor sizing, which occurs at mm-wave frequencies shows an upper limit for a maximum transistor size that can be achieved with a relatively high gain of a single transistor.

In addition, because of the impedance matching, it is more difficult to achieve a sensible power gain from a single-stage amplifier [15]. New topology to overcome this issue need to be explored. At sub-6 GHz and mm-wave frequency spectrum, it is harder to achieve high output power level due to the low supply voltage that accompanies smaller technology nodes. Besides, the technology shrinks cause the gate oxide to become thinner and breakdown voltage to become lower, hence limiting opportunities for better output power at the receiving end of the system [16]. A cascade topology at both spectrums will be explored to overcome this issue. For wireless communication protocols, PAE has recently become an important consideration. The shrinking transistor size and the growing density of wireless devices of the next decade means a decrease in efficiency [7]. High PAE is therefore required to improve the performance of the design. To overcome this issue, a reverse body bias technique is being explore as it offers a better controllability on the drain current which will result in high PAE and improves the performance of the design.

1.4 DEVICE TECHNOLOGY

Nowadays, most of the PAs are developed in III-V semiconductor groups due to breakdown speed, higher frequency responses, and faster market time than silicone-technology. At the current base station, PAs need a reasonably high POUT, and they are mainly built-in using GAN, GaAs, or Laterally Diffused Metal-Oxide Semiconductor (LDMOS) depending on the POUT requirements. For an instant, the GaN system can operate at a 6-8 W / mm RF power density in 4G mobile bands and can provide 3.6 W POUT for pulse mode, whereas their silicone-based counterpart is unable to reach this requirement. But, the silicone-based technology for PAs design has the advantages of offering greater monolithic integration with additional features.

In the coming years, the LTE-Advanced MIMO systems will first be tested to pave way for future 5G mobile networks with a maximum frequency of 6 GHz [7]. Due to the significant variations between cm-Wave/mm-Wave frequency and the massive MIMO vs. 4G LTE, the individual 5G PA usually has less POUT than many of those currently used in 4G LTE. Table 1.1 displays the 5G POUT criteria for large cells and small cells. It can be seen that the 5G PAs used in picocells and femtocells both have relatively lower POUT [2]. On the other hand, a 5G macrocell would possibly need to use GaN or GaAs PA because of their more significant POUT specifications. Robustness, efficiency, and cost ultimately decide the preferred system technology for a specific 5G PA application [2].

Table 1.1 RF POUT requirements for cm-Wave / mm-Wave frequencies [2]

CELL TYPE	RF POUT (dBm)	RF OUT PER PA (dBm)	POTENTIAL PA TECHNOLOGIES
Femtocell	0-24	< 20	CMOS
Picocell	24-30	< 20	CMOS
Microcell	30-40	< 27	GaAs / GaN
Macrocell	40-47	>27	GaAs / GaN