Design Trends for 5G-Advanced Devices and Circuits: New Requirements for RF mmWave Front-End Modules

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Abstract: - In this paper, we study items of 3GPP Release 18/19 5G-Advanced standardized technical specification and trends toward 6G mobile networks. New communication systems require increased functionalities and extreme performance to provide high data rate, reliability, and low latency services. Consequently, with each generation of mobile devices, radio-frequency (RF) front-end module (FEM) architectures grow more complex to support all these requirements. There is a significant trend to maintain a balance between the increased functionality and the added production cost associated with it. Upcoming 5G-Advanced smartphones incorporate new sensing and interface circuitry to accommodate the new RF bands. It is the first generation of mobile devices to utilize millimeter-wave (mmWave) 25-71 GHz band frequencies, supporting bandwidths of several hundred megahertz MHz. For more bandwidth, 6G is expected to utilize higher frequencies from 94GHz to 3THz. However, circuits for mmWave and THz transmitters/receivers are different from those operating at low frequencies up to 100-200 GHz which are satisfactory with today's semiconductor device technologies. As for communication at frequencies above 300 GHz, new technologies are convergent for supporting circuits. This leads to the great cost of production as well as the process of integration. This paper discusses related requirements, design challenges, and possible solutions. Much of the focus is on strategic system partitioning, design of radio access front ends, and leveraging of innovative semiconductor processes. At the core of these devices are highly integrated RF circuits (ICs), multilayer packages, modules, and mixed-signal printed circuit board (PCB) systems. To accommodate these architectures, more advanced densification and miniaturization as well as technology selection is taking place with electronic systems. It is because more theoretical and practical work into higher frequency circuits and systems is needed to improve existing technologies.

Key-Words: - mobile communication, 5G devices, 3GPP, mmWave, RF circuits, front-end modules.

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1 Introduction

The continuous trend for higher data capacity, low latency, and emerging applications in new generation 5G smartphones and mobile devices has been one of the main drivers of semiconductor industry. However, the smartphone industry is a very large volume industry where hardware changes and improvements take a long time to be tested for functionality and reliability before being deployed. That is the significance of timeframes in the 3GPP standardization process, [1].

The third generation Partnership Project (3GPP) is a collaborative project between seven standardization organizations working together to produce global technical reports and specifications for the development and implementation next next-generation networks. Technical reports result from studies conducted by work groups, which are then incorporated into technical specifications for serving as the standard. As a worldwide partnership project, technical specifications later become national standards. In 3GPP, the phased approach is managed using release (R). A release consists of a set of internally consistent set of features and specifications. 3GPP defines R18 and later specifications as 5G-Advanced, [2], [3], [4].

In R18, many of the proposed research and study topics focus on enhancing radio and system performance. It extended the 5G millimeter-wave (mmWave) bands up to 71 GHz with up to 2 GHz modulation bandwidth (BW). It has come with more technical challenges regarding RF interferences and the integration of an increased number of components such as RF switches, acoustic filters, and power amplifiers in a few RF front-end modules (FEM). Also, there is an increase in the number of RF radio transmitters and receivers operating at the same time. Therefore, there is a significant trend to maintain a balance of added cost and size associated with upcoming 5G-Advanced smartphones.

5G is the first generation of mobile communications to utilize millimeter-wave mmWave 25-71 GHz band frequencies, supporting bandwidths of several hundred megahertz (MHz). The trend driven by the need for more available bandwidth, introduces higher propagation losses and smaller geometries. To address greater propagation losses at higher frequencies, 5G and subsequent networks will employ more efficient, intelligent antennas based on Multiple Input Multiple Output (MIMO) transmitters/receivers and beam steering phased array technologies. A highly integrated front-end module (FEM) is one of the most important parts of a 5G RF system, it is placed between the antenna and the digital baseband (BB) section. FEM has several RF components like switches and amplifiers which serve different purposes to make the functioning of the module more efficient and increase its performance. Current activity in mmWave FEM design includes the development of beam steering phased arrays, antenna-in-package (AiP) solutions, beamforming RF integrated circuits (ICs), multi-technology integration, and new linear power amplifier (PA) architectures, [5], [6].

For more bandwidth, 6G is expected to utilize higher frequencies from 94 GHz to 3 THz. The move to higher frequency bands will help reduce the size of these antennas, making efforts to shrink component footprints easier. However, the antennas and package interconnects will be more disposed to parasitic and unintended coupling. Hybrid digital/RF front-end architectures will continue along a development path that supports beam steering, multiple transmit/receive channels and frequency bands, and amplifier linearization techniques. This paper discusses design challenges and possible solutions.

The paper is structured as follows. In the first part, we focus on 5G-Advanced research and study topics for enhancing system and radio performance in mmWave and C-band. In the second part, high data rate and low latency requirements as well as innovative technology for higher-frequency circuits for RF front-end modules are presented.

2 5G-Advanced Standardization

Specifications for the 5th generation mobile communications system (5G) were drafted as 3rd Generation Partnership Project (3GPP) Release 15 (R15) in 2018. These 5G specifications achieved the three technical features of high data rate and high capacity, high reliability and low latency, and massive device connectivity by using even higher frequency bands compared with the past and by giving the system high flexibility enabling the application of a wide range of services.

Since the standardization of R15 as the initial specifications, 5G has continued to evolve in new releases such as R16 (June 2020) and R17 (June 2022) through enhanced functions, new functions, etc. 3GPP defines R18 (June 2024) and later specifications as 5G-Advanced, [7]. In R19 (Dec. 2025), some studies with a view to 6G are beginning on, for example, a channel model for 7-24 GHz frequencies included in the candidate frequency bands for the initial 6G mobile communications system agreed upon at WRC-23 and on radio sensing included in the ITU-R IMT-2030 *Framework Recommendation*. Discussions are also being held in relation to the 6G standardization schedule. The plan is to draft 3GPP R21 (Dec. 2028) as initial 6G specifications and to propose them for IMT-2030, [2].

Positions and features of releases are shown in Table 1. Here, R16 and R17 can be positioned as updates of the initial specification R15. On the other hand, in part of R18 and in R19 and beyond, specifications for new functions were drafted to further expand the application areas of 3GPP, and studies and standardization of new functions were carried out with a view toward 6G, [3], [4].

Table 1. 3GPP R18 position and features

R16 (June 2020) **R17** (June 2022)	**R18** (June 2024) **R19** (Dec. 2025)
commercialization in the first half of 2020s	commercialization in the second half of 2020s
✓addition of functions not included in R15 ✓extensions to major functions toward mmWave, URLLC, NS, NTN, RedCap	✓functional additions and extensions of application ✓new functions and studies with a view toward 6G

The R19 standards will continue to build on the significant topics introduced in R18, such as enhanced coverage and enhanced mobility performance. Also, a number of new studies will be carried out considering the situation with 6G candidate frequencies, [8].

2.1 Increased Throughput, Capacity, Coverage

In R18 5G-Advanced, many of the proposed research and study topics focus on enhancing radio and system performance, [9].

As functionalities for increasing user throughput and system capacity, advanced Multiple Input Multiple Output (MIMO) increases system capacity and user throughput; enhanced handover reduce latency and increase flexibility; enhanced multi-carrier technology improves throughput in multi-carrier operation; and enhanced user equipment (UE) radio frequency (RF) technologies for frequency ranges FR1 and FR2 increase user throughput.

As functionalities for expanding coverage, repetitions PRACH (Physical Random Access CHannel) enhance physical channel coverage, methods improve UpLink (UL) transmission power efficiency, and dynamic waveform switching prevents resetting of RRC (Radio Resource Control) when switching waveform in the UL.

5G-Advanced improves system capacity by increasing a maximum number of users in Multi-User MIMO (MU-MIMO), enhancing UL user throughput through simultaneous transmission, maximum 8-layer data transmission, and CSI (state of the radio channel between base station BS and UE) extension for UEs moving at moderate to high speed. 5G employs more efficient intelligent antennas based on multiple input multiple output (MIMO) and beam steering phased array technologies, introducing cost-effective solutions to realize higher data rates and low latency. Smartphones use MIMO transmitters/receivers and carrier aggregation (CA). Wireless system capacity with k MIMO channels is estimated using the Shannon's formula:

$$C = B_w \sum_{k=1}^{k} log_2\left(1 + \frac{e_n S_k}{N_x + I_k}\right) \quad (1)$$

where B_w is channel bandwidth, S_k is transmitted power for spatial multiplexing level k, I_k is in-band interference on link k, e_k is increased through the use of average envelope/power tracking, and N_x in-band thermal noise.

To achieve higher capacity these are the techniques that are incorporated in 5G-Advanced:

- increase channel bandwidth (5G NR maximum carrier bandwidth is up to 100 MHz in FR1 or up to 400 MHz in the FR2)
- increase the transmit power for spatial multiplexing level (as 26 dBm for high power user equipment UE)
- decrease noise N_x and improve receiver (R_x) sensitivity
- reduce in-band interference I_k on link k, especially in multiple uplink (UL) T_x such as CA and MIMO
- higher order quadrature modulation such as 256 QAM for UL
- increase signal S_k through the use of envelope tracking.

2.2 New RF bands

The trend for more available bandwidth at higher frequencies leads to introduce new bands for 5G/6G. The frequency bands are divided into several frequency ranges (Figure 1, Appendix). FR1 includes all existing 4G bands and new 5G bands and corresponds to sub-6 GHz bands (410 MHz–6 GHz). These bands are the backbone of 5G deployment and carry the bulk of data traffic. The frequency range FR2 includes new mmWave bands (25-71 GHz). Frequency range FR3 comprises 10-20 GHz bands. There are discussions in 3GPP for future use in 5G. The next frequency range FR4 covers 52.6-71 GHz and is expected to be used in autonomous vehicles and vehicular radars. Finally, the frequency range FR5 covers 95-325 GHz and will be part of 6G deployment, [10], [11].

Only a few smartphones now use mmWave modules because of their size, power consumption, increased RF propagation loss, and additional expense. The C-band 3.4-4.2 GHz frequency range facilitates the transition to 5G enhanced mobile broadband (eMBB) by providing access to a range of frequencies with less difficult propagation circumstances and losses. Transmission in a non-line-of-sight (LoS) environment is made possible. As a result, lower-frequency bands can enter indoor spaces more easily. The advantages of C-band over mmWave are both technical and financial since it eliminates the requirement for additional cells when it is superimposed on top of pre-existing macro-cellular or small-cell BS. Additionally, compared to mmWave, the access to a variety of spectrums has less difficult propagation conditions. It should be mentioned that, in contrast to frequency-division-duplex (FDD), which employs paired spectrum with distinct frequencies, C-band uses time-division-duplex technology (TDD), which permits transmission and reception on the same channel.

3 RF Front-End Module Architecture

FEM architectures become increasingly complex and sophisticated with each generation of a communication system in order to meet all the RF requirements. Finding a balance between increased functionality and the corresponding size and cost is one of the most significant trends. The objective is to reduce the cost so that high-frequency systems can be produced in large quantities, [5], [6].

A general communication architecture with system partitioning is shown in Figure 2 (Appendix). FEM front-end module integrates all RF active components (switches, amplifiers, splitters, converters) between the antenna and the digital baseband (BB) section of the 5G modem. In 4G user end devices (UE), antenna, power amplifier (PA), and switches/LNA (low noise amplifier) in FEM are standalone chips to achieve optimized RF performance with special processes. For the 5G mmWave frequency band, the FEMs design and also technology selection are different from 4G designs.

More densification and miniaturization of electronic systems, together with innovations in system-in-package (SiP) design, are required to support the FEM architectures. SiP integrates the optimum active device with any type of passive component. Additionally, it facilitates the combination (mix) of digital integrated circuits (ICs) with analog circuitry and radio frequency RF functionalities. Portable devices are made possible by SiP design, particularly with the requirement of the increasing number of RF functions that need to be integrated, [12].

Figure 3 (Appendix) illustrates a 5G mmWave reference design at the board, package, and chip levels. All blocks before the intermediate frequency (IF) must be integrated into one die in order to reduce the significant package loss. New FEM processes must be developed by the semiconductor industry to satisfy both mmWave and sub-6GHz band requirements. As for packing, it has a significantly greater impact on high-frequency circuits than on low-frequency circuits. There are two related characteristics in circuit design and operation:

- impact of physical packaging, which protects electronic circuits from environmental influences on their frequency high-frequency characteristics
- using packing as a benefit when designing circuits based on the SiP system method.

3.1 High Data Rate and Low Latency Requirements

Reliable high data rates and low latency are important in connecting smart devices in 5G NR New radio. High data rates are made possible by combining mmWave spectrum and sub-6 GHz bands with RF technologies including ultra-wideband (UWB), sensing, and computation techniques. As a result, with every communication system generation, RF front-end architectures get increasingly complex. A typical 5G FEM for mobile devices has 6-9 antennas for sub-6 GHz and mmWave 8/16 channels module.

In order to achieve the high data rate and low latency at the system level, the new requirements for FEM are a lower noise figure for LNA and a higher linearity high data rate for PA. The theoretical data rate (DR) is given by the formula

$$DR = n_s \cdot m \cdot (n_{cc} \cdot n_{sb} \cdot rb) \cdot n_{ss} \cdot n_{sl} \cdot ovh \cdot tdd_{ov} \quad (2)$$

where n_s represents the number of bits per symbol (8 bits for 256 QAM), m represents the number of MIMO data streams, n_{cc} represents the number of component carriers for CA, n_{sb} represents the number of sub-carriers, rb represents the number of resource blocks (RBs), n_{ss} represents the number of symbols per slot, n_{sl} represents the number of slots, ovh (in percentage) is the overhead required for control and coding, and tdd_{ov} represents the TDD duty cycle.

Actual smartphones are equipped with multiple antennas that can cover various frequency bands. The most optimal propagation path for communication with the base station (BS) is the basis for the strategic selection of these antennas. Aperture tuners (ATs) and impedance tuners (ITs) are used to correct for any mismatch and guarantee coverage across several bands. By calculating the maximum signal-to-noise plus interference ratio (SINR), the optimal propagation path is chosen.

Although DL is asymmetric as compared to UL for most smartphone applications, 5G requires UL rates of about 100 Mbps in order to provide a high DL, assuming a 10% UL rate for acknowledge/sync signals. 5G-Advanced has adopted high-power UE which increases the RF power delivered at the antenna to 26 versus 23 dBm for 4G. As a result, the cell coverage radius rises by 20%, and the BS coverage area increases by 40%. More than one transmitter Tx in UL together with several receivers Rx in DL are required by all of these 5G specifications.

All these radios will create RF interferences through conductive and radiated paths. All of the Tx transmitters and other digital clock-related activities in the FEM front-end module induce the intermodulation products. Managing all of these RF interferences is one of the primary design challenges for 5G FEM. Additionally, due to different Rx/Tx configurations between DL and UL and due to high power Tx capabilities for base stations (40 dBm), the RF UL transmission is the weak link. The new 5G bands and higher bandwidth BW make this a problem.

Low latency is the prerequisite for real-time applications, such as autonomous cars, as well as smart machines communicating in real-time. There are significant challenges for FEM:

- increased the linearity requirements for multiple Tx/Rx paths operating at the same time
- maintain at least −38 dBc relative to the carrier adjacent channel power/leakage ratio
- 5G NR introduces high peak-to-average power ratio (PAPR) waveforms
- higher requirements for noise performance.

3.2 RF Circuits Technology

Electronic systems are becoming increasingly densified and miniaturized in order to support complex high-frequency RF front-end architectures. Frequencies up to 100-200 GHz are adequate for modern semiconductor devices. Circuits for mmWave and THz transmitters/receivers, however, differ from those for low-frequency operations. Transistors that operate near their working frequency limit are used in their construction. At high frequencies, passive components such as capacitors and inductors begin to behave differently. Transmission lines, whose length is proportional to wavelength and tend to shrink in size, must be used to replace the components. In order to improve current technologies, additional theoretical and practical research into high-frequency devices and circuits is required, [13].

Regarding communication at frequencies higher than 200 GHz, a number of technologies are coming together to support circuits up to the lower THz range above 300 GHz. This results in high costs for both the integration process and fabrication. It is hoped that emerging technologies, like carbon or graphene nanotubes, will eventually be able to compete with semiconductor technology in terms of operating frequency.

As a nanomaterial, graphene is a member of a class of 2D semiconductors that have a thickness of one or several atom layers. It is made up of a single layer of carbon atoms arranged in a honeycomb pattern. Group IV of the periodic table contains carbon (C), which shares a number of characteristics with Si and Ge. The main characteristics of graphene are carrier mobility (velocity of free electrons/holes in a semiconductor moving under an applied electric field), and high thermal and excellent mechanical characteristics.

Diamond-based electronics is a form of carbon. It is the greatest choice for high-temperature and high-power operation since it has the highest known hardness and thermal conductivity (33W/cm· K). From an electrical perspective, it possesses semiconductor-like characteristics. Additionally, its bandgap of 5.5 eV is roughly five times greater than Si's. The working temperature of the diamond is higher than 1000°C, its electric breakdown field is around 10 MV/cm^3, and its electron mobility is over 2000 cm^2/Vs. On the other hand, there are real-world issues with diamond electronics. Specifically, at ambient temperature, certain diamond transistors do not activate. Before being used commercially, transistors that operate within the range of temperatures still require research, and optimization before any commercial use.

Carbon nanotubes (CNTs), are cylindrical nanoscale objects. They are made from a rolled monolayer sheet that resembles graphene. Cylinders of CNT are nested. The diameter of non-nested structures is roughly 1 nm. It should be mentioned that CNTs have a 1D structure, excellent thermal conductivity, and ballistic electron conduction. The graphene sheet's roll determines whether it is metallic or semiconducting. Regarding the metallic one, nanoscale connections can be employed. On the other hand, depending on the CNT diameter, semiconducting CNTs can be employed with varying band gap energy values and have high carrier velocities of $8 \cdot 10^7$ cm/s. CNTs come in helical, armchair, and zigzag shapes. Armchair CNTs are only semiconducting, whereas zigzag and helical CNTs exhibit either metallic or semiconducting properties. Fabrication of CNTs such as that of graphene transistors needs process improvements and further research.

4 Conclusion

Next-generation 5G/6G mobile communication devices provide massive connectivity with extreme capacity, coverage, reliability, and ultra-low latency, enabling a wide range of new services. Complex RF front-end topologies and highly integrated electronics were used to create a variety of innovative technologies that enabled the required performance. For the advancement of these technologies, RF mmWave design is essential. We highlight relevant requirements, design challenges, and potential solutions. The important trend is balancing increased functionality and added production costs due to new requirements.

The first generation of mobile devices to use millimeter-wave technology is the upcoming 5G-Advanced smartphones. The findings of the 3GPP R18 study on improving system and radio performance point to more effective intelligent antennas based on beam steering phased array and MIMO transmitters/receivers, which offer cost-effective solutions to achieve higher data rates and lower latency.

We point out the significance of using optimal semiconductor techniques, designing RF FEM front-ends modules, and strategically partitioning communication systems. Highly integrated RF circuits (ICs), multilayer packages, modules, and mixed-signal printed circuit board (PCB) systems are the fundamental components of these innovative technologies. Electronic systems should undergo more densification and miniaturization, as well as production technology selection, to support these advanced architectures.

Present semiconductor device production technologies are adequate up to 100-200 GHz. We take into consideration the latest technologies that support RF circuits for communication at frequencies higher than 300 GHz. However this results in high process integration and production costs. It turns out that more future theoretical and practical work into higher frequency circuits and devices is needed to improve existing semiconductor technology.

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APPENDIX

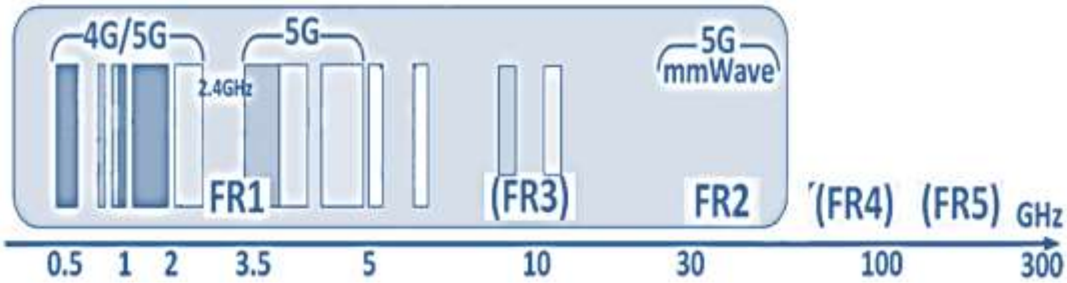

Fig. 1: 4G/5G/6G frequency bands FR1-5

Fig. 2: 5G UE user equipment communication architecture with system partitioning:
Front-end modules integrates all RF active components (switches, amplifiers, splitters, converter), [12]

Fig. 3: 5G mmWave (28 GHz) reference design on board, package, and chip level:
printed circuit board (PCB), multilayer package (LTCC), and RF integrated circuits (IC 45nm), [13]

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