OPPORTUNITIES AND CHALLENGES OF MMWAVE NR

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INTRODUCTION

The realization of a seamless, fully connected world requires enhancements to our current communications technology, from both a network infrastructure perspective and a user equipment (UE) perspective. These demands are directly driven by the consumer's expectations, application requirements, and saturation of frequency bands used in current spectrum.

The fifth generation (5G) of mobile communication networks, and specifically millimeter-wave (mmWave) New Radio (NR), aims to enable this future with ultra-low-latency, ultra-wideband services, opening up a whole new era of applications and services, much like 4G Long Term Evolution (LTE) did a decade ago. To enable 5G, the Third Generation Partnership Project (3GPP) is focusing on defining the technical specifications for NR technology, as well as enhancements to the current LTE. However, enabling and launching 5G NR presents both technological opportunities and challenges.

In this column, we explore how 5G mmWave challenges are being approached in 3GPP standardization and how solutions can enable the technology to help achieve broader bandwidths and harness some of the inherent benefits of higher-frequency communications.

5G NEW RADIO

5G aims to bring several benefits over 4G LTE, including faster speed, ultra-reliability, lower latency, and increased connectivity. Many of the early 5G use cases will fall into the realms of enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), ultra-reliable and low-latency communications (URLLC), as well as vehicle-to-everything (V2X) communications. The finalization of the first 5G standard, the 3GPP Non-Standalone (NSA) 5G standard, at the December 2017 RAN plenary meeting marked a momentous milestone for 5G. At the following June 2018 plenary meeting, the Standalone (SA) 5G standard was concluded. The latest drops of Release 15 included NR-NR dual connectivity and NR-E-UTRA dual connectivity, and were introduced at the December 2018 RAN plenary meeting.

Governments and regulators around the globe have also been working to meet challenges faced by current communications by opening up new spectrum for 5G NR. Initial mmWave deployments are expected in 28 GHz (3GPP n257 and n261) and 39 GHz (3GPP n260), followed by 26 GHz (3GPP n258). Other bands are expected to be opened as the demand for more NR services continues to rise. NR spectrum is discussed in greater detail next.

NR BAND SPECTRUM

Within 3GPP, Working Group 4 (known as RAN4) is in charge of deriving the minimum requirements for both transmission and reception related parameters and requirements. For 5G, this task begins in defining the relevant spectrum for NR, which was divided into two frequency ranges. The first range, frequency range 1 (FR1), extends from 450 MHz to 6000 MHz [1]. The second range, frequency range 2 (FR2), covers 24.25 GHz to 52.6 GHz [1], with current specifications defined up to 40 GHz [2]. The technical specifications of core requirements for FR1 and FR2 are found in TS 38.101-1 [3] and TS 38.101-2 [2], respectively. For NR, it is precisely the FR2 specifications that will enable mmWave communications and where the rest of this article will focus. We note that since FR2 includes frequencies above 30 GHz, the terms mmWave and FR2 are oftentimes used interchangeably. Table 1 lists the bands currently defined in FR2.

Band name	Frequency range (MHz)
n257	26,500–29,500
n258	24,250–27,500
n260	37,000–40,000
n261	27,500–28,350

TABLE 1. NR FR2 bands.

In NR, FR2 boasts a large amount of spectrum, which greatly exceeds the amount of spectrum in FR1. Therefore, supporting mmWave operation is an essential component to provide very high capacity and data rates for eMBB use cases and ensure the best user experience. However, FR2 operation brings multiple technical challenges that need to be solved from both NR standard development and product design perspectives. The support of multiple bands with largely separated carrier frequencies requires proper handling from RF and antenna design. A substantially increased aggregated channel bandwidth, with up to 400 MHz bandwidth of a single carrier and more than 1 GHz for the carrier aggregation scenario, puts pressure on both RF and baseband UE capabilities. Also, a considerable increase in phase noise level for mmWave should be properly handled at the UE side to guarantee that high order modulations can be supported. Finally, FR2 is characterized by a significantly larger wireless link propagation loss, which can be compensated by the support of multi-element antenna arrays at both the network and UE sides, along with using analog beamforming techniques to ensure that a sufficient coverage level can be achieved. To understand how these challenges were addressed in the specifications, we examine how the FR2 requirements were defined in 3GPP.

FR2 REQUIREMENTS

With clearly defined bands in FR2, we can now discuss how the performance requirements of devices operating in those bands were derived. From a UE perspective, the form-factor size and its specific material properties will, to a significant extent, dictate the performance. A smaller device, like a cell phone, is more restricted in size, and thus integration is more challenging. Larger devices allow a greater number of antenna elements to be integrated, and the space makes integration easier. Because of this difference, and to support all the devices that address current market demands, power classes were defined with a UE type in mind. Table 2 summarizes the four power classes currently defined for FR2 NR.

In 3GPP, a power class is a package of four parameters: the minimum peak effective isotropic radiated power (EIRP), the minimum spherical EIRP, a maximum transmission radiated power (TRP), and the regulatory-defined maximum EIRP. A maximum TRP is chosen to limit co-channel interference, while the maximum EIRP is a parameter set by the FCC for RF exposure (RFE) compliance. RAN4 approved the minimum peak EIRP and minimum spherical EIRP requirements after careful discussion and consideration of typical architectures, and integration challenges at mmWave frequencies. Given that handheld UEs (PC3) have the smallest form-factor and present the biggest integration challenge, we focus on how its requirements were approached in RAN4 discussions.

Power class	UE type	Description
PC1	Fixed wireless access (FWA) UE	FWA devices are fixed on a stationary platform (wall); FCC allows up to 55 dBm max EIRP for these devices (which they refer to as *transportable*)
PC2	Vehicular UE	Vehicle-mounted UE (fixed device on a moving platform)
PC3	Handheld UE	Smallest form-factor of all power classes
PC4	High-power non-handheld UE	High-power UE (mobile and fixed operation)

TABLE 2. FR2 power classes.

A comprehensive list of parameters was used in the link budget calculations to derive the minimum peak EIRP requirements [4]. For PC3, the antenna architecture assumption was a 4-element patch antenna array. Because we are deriving minimum requirements, the value used for each parameter in the link budget is based on the expected worst case rather than nominal. Beyond the antenna architecture, companies provided data for PA output power, gain variations in the desired bandwidth, and implementation losses [5]. The latter includes losses due to the integration of the antenna array in the form-factor, along with mismatch and transmission line losses. This means that the impact of material properties and irregularities are taken into account, as well as any variations in the fabrication process. Considering the complexity behind characterizing the implementation loss parameter, it is not surprising that aligning on a value for this parameter proved difficult during discussions. Ultimately, the final approved values for the requirements of the 28 GHz bands (n257, n258, and n261) and 39 GHz band (n260) were based on consensus.

For mmWave frequencies, it is not sufficient to guarantee an expected power in a single direction. For coverage, it is important for the UE to maintain a reliable link over a set of directions. This aspect is captured in the spherical coverage parameter of a power class. Considering the UE type of each power class, a cumulative distribution function (CDF) of the EIRP was created for this requirement. Ultimately, the spherical coverage definition included a percentile point in the CDF and the minimum EIRP value for that point.

Two main issues were addressed through the performance requirements defined for FR2. The first focused on the design and implementation challenges, while the second ensured the support of different UE types. Beyond establishing the requirements for standards specification, it is important to discuss how the performance of these devices will be tested. The upcoming section addresses this topic.

DEVICE TESTING

Developing mmWave capable devices requires proper modeling of the integrated design, and measurements to assess the performance of the device and help validate the models used. Additionally, mmWave operation brings substantial challenges to device performance testing and verification, therefore it has strong implications on the UE development and certification processes. Due to their high operation frequency, mmWave devices are characterized by a very high level of integrated components. To minimize RF implementation losses, antenna arrays are tightly integrated with the RF front-end, and conventional RF antenna connectors (which are usually available for low-frequency NR and LTE devices) are not available for NR mmWave devices. As a consequence, conventional conducted testing and verification methodologies, where the test equipment is connected directly to the UE RF connectors, are no longer applicable for highly integrated designs. To overcome this problem, NR mmWave conformance testing and verification will be done in a radiated, over-the-air (OTA) environment inside an anechoic chamber. With these challenges in mind, 3GPP developed a new dedicated OTA methodology to test mmWave requirements, which will be used as a common approach for NR mmWave conformance testing.

The OTA testing topic has a long history in 3GPP, with a wide set of requirements and test methods previously introduced for LTE technology [6,7]. However, the methods were developed in application to sub-6 GHz carrier frequencies and NR mmWave operation brings additional challenges, including a very high path loss, a vast range of different device types, and the need for testing support of a wide set of requirements for both RF and baseband functionality. 3GPP leveraged the work previously done for LTE and introduced a set of new baseline radiated test methods for mmWave [8]. The new test methods mainly rely on either direct far field (DFF) or indirect far field (IFF) setups and provide procedures to enable verification of UE RF, radio resource management (RRM), and UE demodulation performance.

Due to OTA nature, the developed test methods are applicable to mmWave-capable devices (e.g., smartphones) rather than wireless chipsets alone and strive to ensure reliable end-to-end performance in real field conditions. Testing challenges are mainly driven by highly integrated and complex device designs, which are described in the next section.

PRODUCT DESIGN IN FR2

One of the key challenges for 5G is the integration of mmWave solutions into a mobile form-factor. Area restrictions, thermal limitations, battery life, and acceptable RF exposure are all factors that must be considered during design and in some cases require innovative solutions. The importance of co-design of silicon and form-factor device hardware will only increase at mmWave frequencies.

ARRAY SIZE CONSIDERATIONS

A fundamental trade-off for mmWave solutions is the array size for beamforming gain vs. conducted output power per element. While it is more efficient to increase EIRP by increasing the array size, form-factor area restrictions will likely limit this for the majority of mobile devices. Although 3GPP does not dictate the size of arrays to be used in devices, for PC3, the underlying assumption is a 4-element array as this is expected to be a realistic size for most mobile device applications. Increasing conducted output power also has limitations as power dissipation creates heating in the device, and thermal issues could become a restriction. Solutions that can efficiently deliver higher conducted output power will be very attractive in order to achieve EIRP requirements in a small form-factor.

Techniques like digital pre-distortion (DPD) or envelope tracking (ET) are interesting topics for mmWave to improve the efficiency at higher output powers. However, mmWave also presents a challenge for applying these techniques as the signal bandwidths are significantly wider with up to 400 MHz bandwidth per component carrier. In addition, there is the challenge of applying pre-distortion or envelope tracking across multiple PAs, making these topics a strong opportunity for innovation.

It is also important to note that while transmit output power is a key trade-off for the array size, there is also a similar challenge for the receiver as well. In order to meet EIS requirements, a smaller array size translates into lower conducted noise figure targets. In both the transmitter and receiver cases, the routing losses

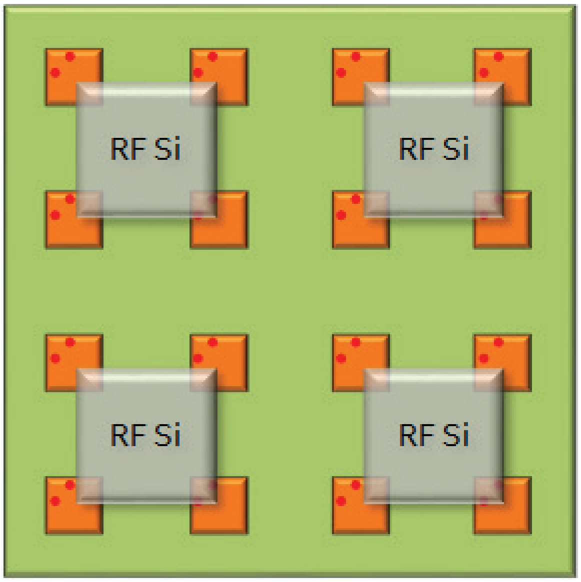

FIGURE 1. Example of a modular mmWave silicon solution.

between silicon and antenna elements become a critical factor for efficient output power and low noise figure. The co-design of the silicon and the antenna array for optimizing these routing lengths is an important factor. Figure 1 is an example of how a modular solution can be implemented to enable scaling of array sizes and short routing distances to antenna elements.

SOLUTION SCALABILITY

While the 3GPP assumption for PC3 is a 4-element array, it is also important to have the flexibility to support larger array sizes. This is needed both for PC3-classified devices that have the area to support larger arrays and for supporting other power class devices. Figure 2 demonstrates Intel-developed 28 GHz mmWave array solutions using the same chipset for different applications and array sizes. The modules shown in Fig. 1 represent solutions for various UE types and power classes. For mobile devices, a 5 × 2 dual-polarized array is shown, but the chipset also enables efficient scaling down to 4-element arrays for the majority of mobile solutions. An example is also shown of a 4 × 4 dual-polarized array developed for automotive applications, which require a higher output power class (PC2). Lastly, an 8 × 8 dual-polarized array developed for FWA applications is shown; this array would target PC1 classified devices.

CONCLUSION

5G NR technology, particularly its mmWave range, aims to revolutionize modern communications. While there are technical challenges to overcome, standardized solutions will soon enable a whole new world of low-latency, ultra-broadband applications and services. Although current implementation focuses on mmWave bands in the range of 24–40 GHz, the world will soon see an extension to even higher frequency bands with even more available bandwidth. This will allow us to envision a world with seamlessly connected networks delivering content and user experience previously not thought possible.

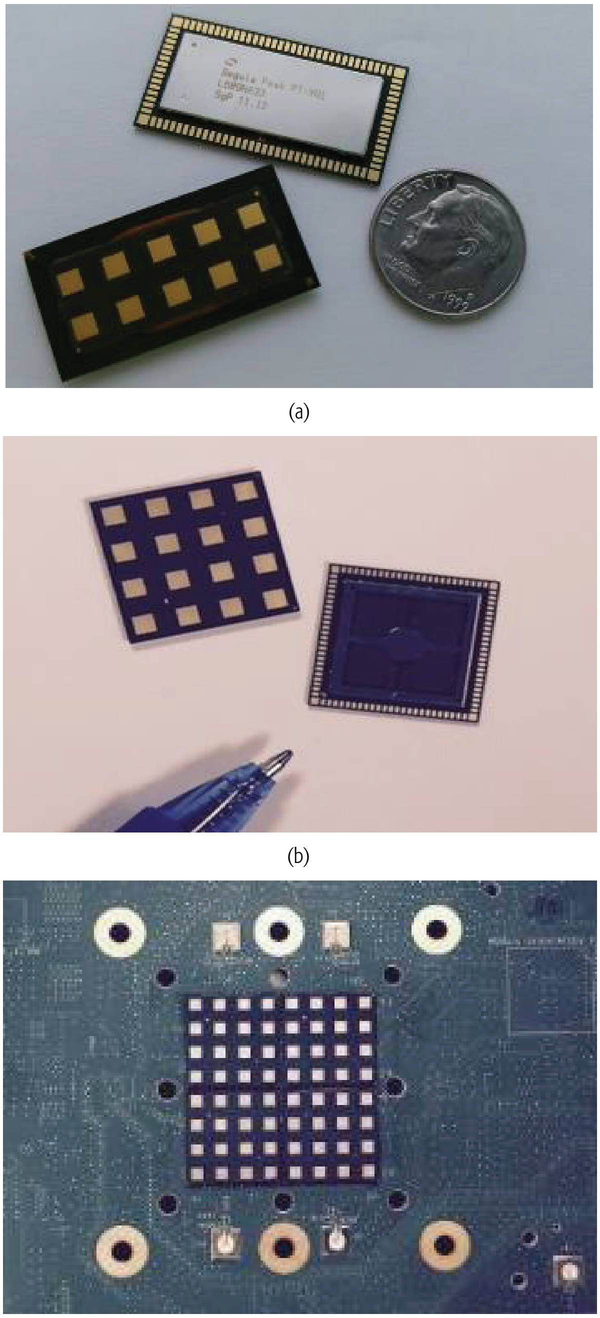
(a)

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FIGURE 2. 28 GHz module solutions for different applications: a) 5 × 2 dual-polarized array module for mobile devices; b) 4 × 4 dual-polarized array module for automotive; c) 8 × 8 dual-polarized array module for CPE.

REFERENCES

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