First Steps in 5G
Overcoming New Radio Device Design Challenges Series

Part 1: 5G New Radio Standard

5G is rapidly approaching and offers a dramatic improvement over 4G’s capabilities. With 5G New Radio (NR) initial release 15 in December 2017, the physical layer specifications are shaping up. Release 15 specifications focus on enhanced mobile broadband (eMBB) and ultra-reliable, low-latency communications (URLLC) to achieve very fast data rates and provide very low latency in wireless communications.

These new specifications introduce new challenges for device and component designers. Besides designing to the new standards, how do you validate protocols for the many different test cases, and verify RF performance so you can deliver the expected quality of service? Measurements now become more challenging. Massive MIMO and beam steering introduce challenges in beam management; use of millimeter-wave (mmWave) frequencies pose challenges in signal quality; and tests that used to be done with cables, now need to be done over-the-air (OTA), which makes validation even more difficult. This four-part white paper series explores the lower layers of the communication stack and considerations for addressing new challenges in designing and testing 5G devices.
Embracing 5G

Emerging technologies such as cloud computing, artificial intelligence (AI) and machine learning, augmented and virtual reality, the Internet of Things, and billions of connected devices are pushing the boundaries of the wireless communications system like never before. Where and how does 5G NR fit? 5G technology promises faster, reliable, and near-instant connections that will universally connect people. Live events and games can be experienced in real time, phone and video calls will feel close and intimate, and smart devices paired with AI will create a customized and personalized environment for everyone.

5G NR is expected to work alongside 4G and even utilize the 4G core network for both data and control planes in non-standalone mode (NSA). It is also expected that 5G, 4G, and Wi-Fi will coexist on the same carriers and utilize unlicensed bands to increase capacity below 6 GHz. 5G NR release 15 sets the foundation to enable flexibility to accommodate future releases of 5G communications. The physical layer is the first step in the adoption of 5G NR and is important because it defines the structure that makes up the radio signal and how the signal is communicated through the air interface.
New Challenges Ahead

The challenges associated with implementing device designs in the physical layer include:

- Flexible time and frequency intervals enable low latency but result in complex channel coding, signal-quality challenges, and numerous test cases.
- Efficient use of spectrum is provided through bandwidth parts, but this introduces new coexistence issues.
- Massive MIMO and mmWave beam steering enable higher throughput and capacity gains, but also introduce new challenges in beam management.
- Use of mmWave frequencies allows for greater channel bandwidths, but introduces new challenges in signal quality and the need for OTA tests.

Part 1 in this series introduces the 5G NR specifications and describes new features that will enable advances expected in 5G. Future installments will dive deeper into the challenges of implementing 5G NR specifications.

5G NR Specifications

NR release 15 specifies a new air interface to enable higher data throughput and low latency use cases. Key to enabling higher data throughput is the addition of mmWave spectrum up to 52.6 GHz. At these higher frequencies, there is more contiguous spectrum available to send more data through the channel. Release 15 specifies a maximum carrier bandwidth up to 400 MHz and up to 16 component carriers that can be aggregated up to 800 MHz of bandwidth. Also, flexibility and scalability in the slot structure will help support the many new and diverse use cases expected in 5G. Figure 1 maps out how different specifications will contribute to delivering a flexible and scalable physical layer and shows the distinct advantages that 5G NR will enable.

Figure 1. 5G NR release 15 technologies and their benefits.
Flexible Waveform and Numerology

5G NR has defined CP-OFDM (cyclic prefix OFDM) to be used as the modulation format (or waveform) in the downlink (DL) and uplink (UL). CP-OFDM use is well-known for DL transmissions but is new for UL transmissions in mobile. Having the same waveform in both UL and DL can enable easier communication for device-to-device communication in future releases. DFT-s-OFDM (delay spread OFDM) has also been specified as an optional waveform in the UL. This uses a single transmission, which is helpful in power-limited scenarios.

Unlike 4G, NR allows for scalable OFDM numerology (µ) where the subcarrier spacings are no longer fixed to 15 kHz. With NR, subcarrier spacing is governed by $2^\mu \times 15$ kHz subcarrier spacings. 15, 30, and 60 kHz subcarrier spacings are used for the lower frequency bands, and 60, 120, and 240 kHz subcarrier spacings are used for the higher frequency bands. Scalable numerology enables scalable slot duration to optimize for different service levels in throughput, latency, or reliability. Larger subcarrier spacing at the higher frequencies also helps with the robustness of the waveform since integrated phase noise can be an issue in mmWave designs. Figure 2 shows how the different subcarrier spacings and the associated transmission time interval (TTI) with each can scale the size of the slot.

![Subcarrier Spacings Diagram](image)

**Figure 2. Relationship between subcarrier spacings and time durations.**

In an OFDM system, cyclic prefix (CP) is used to mitigate the effects of channel delay spread and intersymbol interference. CP provides a buffer to protect the OFDM signal from inter-symbol interference by repeating the end of the symbol at the start of the same symbol. While this reduces the achievable data rate, it completely eliminates the inter-symbol interference up to the length of the CP. In 5G NR, as subcarrier space changes, the cyclic prefix length also scales accordingly, making it possible to adapt the CP length to the channel conditions.
Low Latency Mini-Slots

Ultra-reliable low latency communications (URLLC) is one of three primary 5G use cases and is achieved partially through mini-slots. In LTE, transmissions adhered to the standard slot boundaries, but they are not optimized for minimal latency. A standard slot has 14 OFDM symbols shown in dark blue in figure 3. As the subcarrier spacing increases, the slot duration decreases as shown in light blue. A mini-slot is shorter in duration than a standard slot and can be located anywhere within the slot. A mini-slot can be 2, 4, or 7 OFDM symbols long. Mini-slots can provide low latency payloads with an immediate start time without needing to wait for the start of a slot boundary.

Flexible Slot Structures

NR subframe structure also allows for dynamic assignments of the OFDM symbol link direction and control within the same subframe. By using this dynamic-TDD mechanism, the network can dynamically balance UL and DL traffic requirements and include control and acknowledgment all in the same subframe. The slot format indicator (SFI) is used to denote whether a given OFDM symbol in a slot is used for uplink, downlink, or flexible.

![Diagram of slots and mini-slots within a subframe and their associated slot duration time.](image)

Figure 3. Slots and mini-slots within a subframe and their associated slot duration time.

![Diagram of slot structure to dynamically improve traffic.](image)

Figure 4. Slot structure can be mixed to dynamically improve traffic.
Flexible Bandwidth Parts

In LTE, carriers are narrower in bandwidth, up to 20 MHz maximum that can be aggregated together to create a wider channel bandwidth, up to 100 MHz. In 5G NR, the maximum carrier bandwidth is up to 100 MHz in FR1 (up to 24 GHz), or up to 400 MHz in FR2 (up to 52.6 GHz). New in 5G NR are bandwidth parts where the carrier can be sub-divided for different purposes. Each bandwidth part can have its own numerology and is signaled independently. One carrier can have mixed numerologies to support a mixed level of services like power saving or multiplexing of numerologies and services in unlicensed bands. However, only one bandwidth part in the UL and one in the DL are active at a given time. Bandwidth parts will support legacy 4G devices with new 5G devices on the same carrier. With 4G, 5G, and potentially Wi-Fi multiplexing services, both in- and out-of-band emissions must be kept to a minimum. Figure 5 shows some examples of how bandwidth parts can support different services in a given carrier.

Bandwidth Parts

Figure 5. Bandwidth parts can support multiplexing of different services on the same carrier.
Greater Throughput through Massive MIMO and Beam Steering

Just like any previous generation upgrades, throughput is key to making 5G communications successful. This is achieved in multiple ways including using wider overall channel bandwidths to allow for more data to be sent through the air interface; spatial multiplexing where multiple independent streams of data are sent through multiple antennas at a given time and frequency; and by using enhanced channel feedback, which improves throughput since the signal is optimized for transmission with advanced channel coding to deliver the higher throughput. Massive MIMO and beam steering are key technologies to improving throughput.

NR release 15 specifies frequency use up to 52.6 GHz with up to 400 MHz bandwidth per carrier, and multiple carriers can be aggregated for up to 800 MHz channel bandwidth. Operating at mmWave frequencies, however, introduces new challenges in path loss, blockage, and signal propagation. Beam steering will be a key technology used to overcome these issues. NR specifies new initial access procedures to ensure alignment of the directional transmissions used in beam steering. As shown in figure 6, new initial access techniques where the base station uses beam sweeping to transmit multiple beams, identify the strongest beam, and establish a communication link. Validating initial access, beam management, and throughput achieved through the wireless link will be key factors for successful beam steering implementation in 5G.

Figure 6. Beam sweeping and initial access.
CSI to Improve Beamforming Reliability

Channel state information (CSI) will help with 5G NR beamforming reliability. 5G NR specifies a new beam management framework for CSI acquisition to reduce coupling between CSI measurements and reporting so that different beams can be dynamically controlled. CSI uses channel estimation to intelligently change the precoding and adapt the beam to a specific user. The better and more precise this CSI information, the better this link adaptation will be.

A 5G NR Waveform

It’s important to understand the frequency-, time-, and modulation-domain analysis of the 5G NR waveforms. Having software and hardware that can create and analyze a 5G waveform for the many different use cases at sub-6 GHz and in the new mmWave frequencies with greater bandwidths is essential. New capabilities in NR specifications, including flexible numerologies with different subcarrier spacing, dynamic TDD, and bandwidth parts, add to the complexity of creating and analyzing the waveform. Shown in figure 7 are two different NR waveforms created using Keysight’s 5G Signal Studio software and signal generators and the associated analysis done by Keysight’s 89600 VSA NR software.

Figure 7. Using 5G signal generators, signal analyzers, and VSA software to analyze 4G and 5G waveforms.
Conclusion of Part 1

5G will offer many advances in throughput, low latency, and massive machine-to-machine type communications. The initial 5G NR release 15 provides flexibility and forward compatibility, but with this comes significant challenges in the implementation. Along every measurement step, either through simulation, design, or validation, there are considerations and challenges in meeting these standards. Design and test for 5G devices must evolve to accommodate validation of the many test cases that will be required, to ensure a robust, high throughput connections at mmWave frequencies, and to design for coexistence of 5G NR with 4G and Wi-Fi. Stay tuned for the next installment of the 5G NR white paper where we will review the challenges with implementation in the mmWave frequencies and considerations for your 5G NR device design.

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