WHITE PAPER

5G New Radio:

Introduction to the Physical Layer

CONTENTS

Introduction

To understand the three broad use cases that 5G wireless technology seeks to transform (Figure 1), consider a typical morning office commute in a 5G-connected car just a few years down the road. The vehicle is constantly exchanging position, behavior, and system status information with nearby vehicles, the surrounding highway infrastructure, and traffic control centers. Doing so in a fast and reliable manner augments the car's awareness of its surroundings and allows the driver to turn the steering, accelerating, and braking functions over to the car's semiautonomous driving system. He can now focus on the morning's first conference call.

The driver's team is trying to find the root cause of a turbine malfunction. He puts on his augmented reality (AR) set, and a wireless 4K video feed of an airplane turbine overlaid with sensor data and gauge readings fills his screen. Collaborating in real time with a group of engineers in three different countries, the team guides a technician to isolate one of the components and recommends a troubleshooting procedure.

A few minutes later, when his intelligent-highway exit comes up, the driver takes back control of the car, switches over to a low-bandwidth voice-only connection, and drives into work. The car guides him to the closest available parking spot with an electric charging station. The parking sensor at that spot detects his car and updates the parking availability information on the network. When he plugs in the car to charge, the charging terminal establishes a low-data-rate connection to verify his account and process payment.

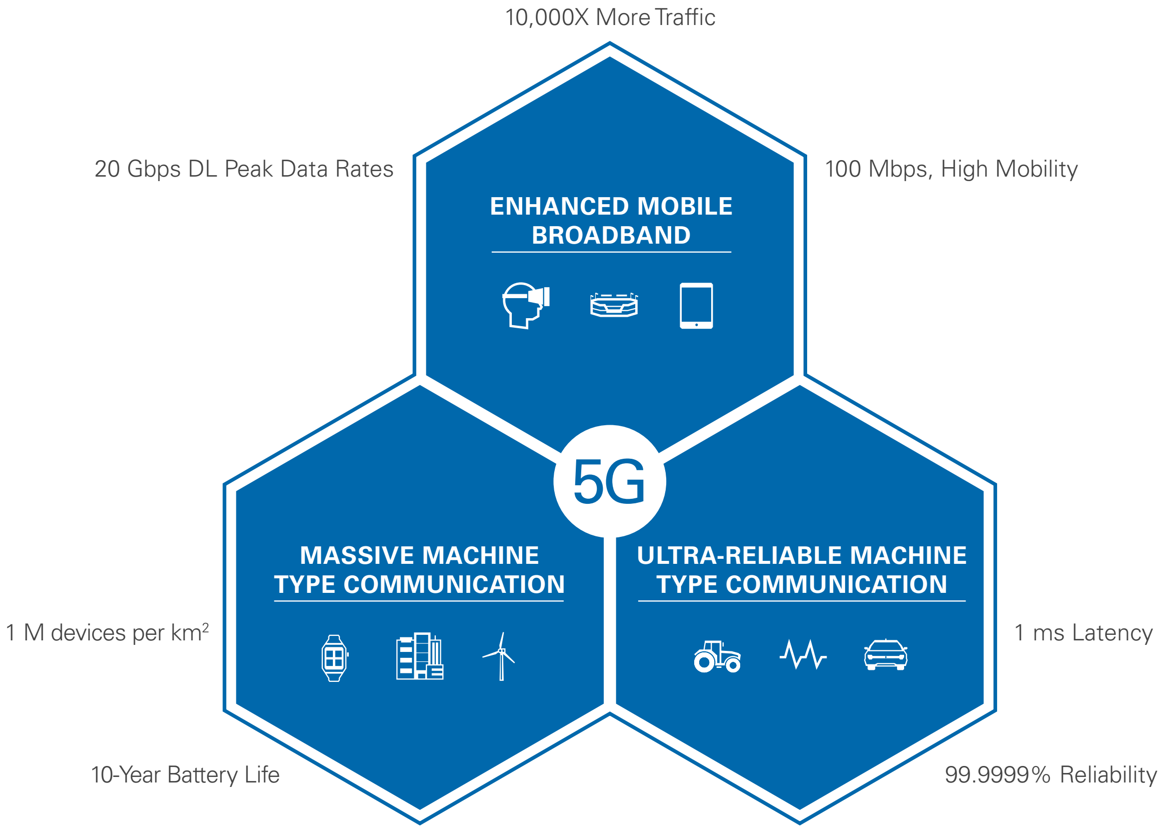


Figure 1. 5G Use Cases and Targeted Key Performance Indicators

Enhanced Mobile Broadband (eMBB) seeks to significantly improve the data rate, latency, user density, capacity, and coverage of mobile broadband access to allow the live streaming of AR/VR applications, even in more crowded environments, such as the intelligent highway the driver uses. Ultra-Reliable Low-Latency Communication (URLLC) enables users and devices to communicate bidirectionally with other devices while generating minimal latency and guaranteeing high network availability. Finally, Massive Machine-Type Communication (mMTC) makes it possible for many low-cost, low-power, long-life devices to support applications such as embedded highway sensors, parking sensors, and smart utility meters.

The requirements of these distinct use cases pose complex technical trade-offs, which involve delicate design decisions. To guarantee interoperability and global access to 5G, the International Telecommunication Union (ITU), an international union of telecommunication industry players, national and regional standards development organizations, regulators, network operators, universities, and research institutions, must approve the standards for 5G technologies. The ITU-R (the radiocommunication sector), the ITU-T (the standardization sector), and the 3GPP (3rd Generation Partnership Project between groups of telecommunications associations that standardizes cellular wireless access) are working concurrently toward a unified 5G New Radio standard. The 3GPP expects to complete Phase 1 by June 2018 with Release 15, which will focus on the eMBB and URLLC use cases. Around the end of 2019, Phase 2 will add functionality to 5G to support more services, large IoT deployments, and much higher frequency bands beyond 52.6 GHz.

For now, the standards bodies have reached fundamental decisions with the Release 14 study phase, including the current focus on non-stand-alone operation of NR to support only the eMBB and URLLC use cases. NR does this by relying on existing 4G infrastructure, the EPC (enhanced packet core) and the eNodeB acting as the Master cell, and the 5G gNodeB (gNB) providing secondary access (based on the dual connectivity principle, as Figure 2 shows).

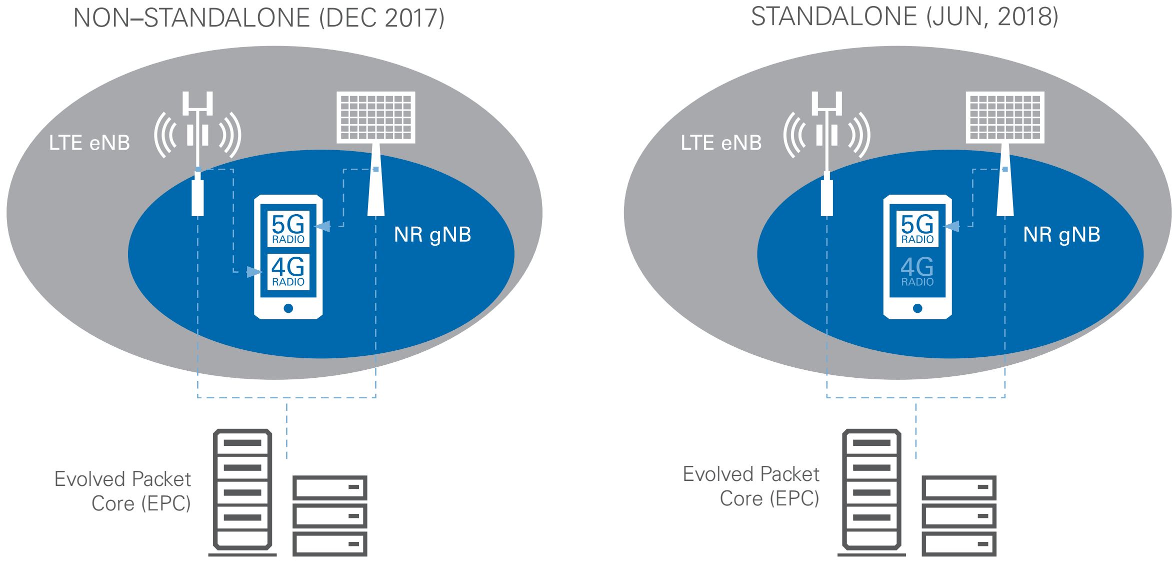


Figure 2. Non-Stand-Alone Versus Stand-Alone Operation

Furthermore, the IEEE has a 5G track that oversees the direction of future developments that existing and new IEEE technologies will need to support 5G targets. These include 802.11ax and 802.11ay (WLAN), 802.15 (short range technologies), and 802.22 (fixed wireless broadband).

A key point to keep in mind is that Release 15 breaks compatibility with 4G standards. This is similar to how 4G standards (LTE) departed from 3G wireless standards (UMTS). Yet, the designers of the NR standard planned for future 5G releases to maintain compatibility with the initial 5G NR specification. Because designers, industry experts, and the market haven't defined all the possible new uses for 5G technology, the 5G physical layer needs to be flexible. This paper presents an introductory tutorial to the 5G physical layer and its implementation to support the key 5G target applications of eMBB and URLLC.

PHY Design Considerations

Many researchers from industry and academia are actively working on addressing the requirements for a robust and reliable 5G implementation. The following key features have played a defining role in the 5G NR physical layer:

- Supporting a wide range of operation bands, a variety of channel bandwidths within those bands, and multiple deployment options.
- Serving applications with very low latency, which requires short subframes and puncturing and bursty interference from mission-critical transmissions.
- Sharing the spectrum dynamically to provision uplink (UL), downlink (DL), sidelink, and backhaul links.
- Implementing multiantenna technology (multiple input, multiple output or MIMO) for larger spectral efficiency.
- Maintaining tight time operation and more efficient frequency use for better time division duplex (TDD) and frequency division duplex (FDD) deployments.
- Having symmetrical DL and UL requirements to enable operation at millimeter wave (mmWave) frequencies of compact, low-cost base stations.

Waveforms for 5G NR

CP-OFDM: Downlink and Uplink

Recently, researchers have been investigating many different multicarrier waveforms and proposing them for 5G radio access. However, because orthogonal frequency division multiplexing (OFDM) implementations lend themselves well to TDD operation and delay-sensitive applications, and because they have demonstrated successful commercial implementation by efficiently processing ever-larger bandwidth signals, cyclic prefix (CP) OFDM became the preferred choice for NR. The strong benefits of CP-OFDM that make it a great fit for 5G implementation are:

High Spectral Efficiency—This essential feature of OFDM access helps meet the extreme data rate needs, especially for backhaul links. Also, in future cases like vehicular communication in dense urban environments, high spectral efficiency will help address capacity constraints when many users broadcast periodically and asynchronously.

MIMO Compatibility—Both base stations and mobile devices will take advantage of MIMO technology to implement spatial and frequency multiplexing with Single-User MIMO and

Multiuser MIMO (MU-MIMO). MIMO deployments also overcome high propagation losses and extend coverage range with beamforming.

Phase Noise Resistance—As the frequency of operation (and with it the oscillator phase noise) increases, an OFDM system can minimize intersymbol interference due to phase noise by applying larger OFDM subcarrier spacing (SCS).

Transceiver Simplicity—OFDM transceivers offer lower implementation complexity compared with other waveforms that designers considered for 5G deployments. Having worked with OFDM designs for several years, the wireless industry knows that their well-understood operation and wide commercial deployment can enable 5G devices with powerful OFDM baseband processing at lower prices.

Channel Time- and Frequency-Selectivity Resistance—With the right selection of SCS and frequency of operation, an OFDM system can finish a transmission between devices in an interval shorter than the channel coherence time and enable high-mobility (high-speed) and high-data-rate scenarios while minimizing the effects of time selectivity. Also, as Figure 3 shows, with channel estimation and equalization techniques, OFDM waveforms demonstrate great resiliency against frequency-selective channels.

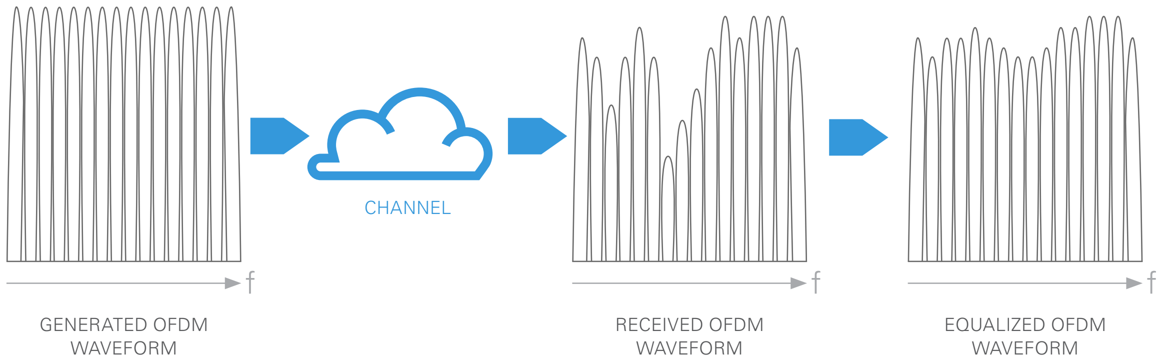


Figure 3. Representation of an OFDM Waveform's Frequency-Selectivity Resistance

Timing Error and Intersymbol Interference Resistance—Because of the CP, a receiver can better tolerate synchronization errors and prevent the previous OFDM symbol from smearing into the currently received OFDM symbol. Figure 4 shows two subsequent OFDM symbols, each with a dedicated CP. The CP at the beginning of each OFDM symbol contains a copy of the end of the OFDM symbol. When the receiver demodulates the signal, it operates on the symbol after the CP (FFT window). This mechanism prevents intersymbol interference between adjacent OFDM symbols

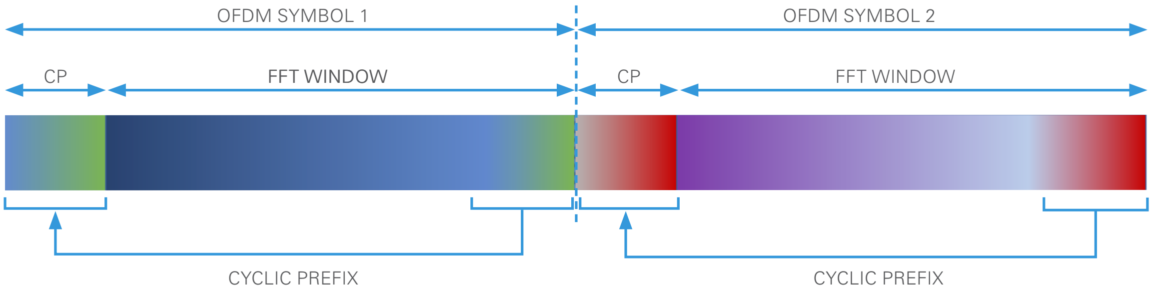


Figure 4. A Cyclic Prefix Separates OFDM Symbols

With CP-OFDM, user equipment (UE) supports the following modulation schemes:

- QPSK
- 16-QAM
- 64-QAM
- 256-QAM

DFT-S-OFDM: Higher Efficiency Uplink

One of the main drawbacks of OFDM waveforms is their high peak-to-average power ratio (PAPR). As a result, RF output power amplifiers on transmitters lose efficiency and can't minimize high-order, nonlinear effects well. For UE such as smartphones, preserving battery life and being energy efficient is important. The RF power amplifier that transmits the signal to the base station consumes the most power within the mobile device, so system designers need a type of waveform that promotes high-efficiency amplifier operation while meeting the spectral demands of 5G applications. Although single-carrier waveforms have very low PAPR and more efficient power amplifier operation, they don't offer high spectral efficiency and dynamic spectrum utilization, their compatibility with MIMO systems is lower, and they are susceptible to frequency-selective channels.

For uplink, NR allows UEs to use CP-OFDM or a hybrid format waveform called discrete Fourier transform spread orthogonal frequency division multiplex (DFT-S-OFDM). In DFT-S-OFDM, the transmitter modulates all subcarriers with the same data. The right side of Figure 5 shows that the first group of subcarriers (all red) takes the same amount of bandwidth as the OFDM symbol on the left. The DFT-S-OFDM modulator maps the same data to all subcarriers but for a shorter duration. It then maps the next data symbol (green) to all subcarriers for another short interval. By the end of the equivalent OFDM symbol time, the transmitter sends the same amount of data as it sends with an OFDM waveform by mapping the data symbols to all subcarriers simultaneously but with shorter transmission intervals. This DFT-S-OFDM waveform combines a lower PAPR with the multipath interference resilience and flexible subcarrier frequency allocation that OFDM provides.

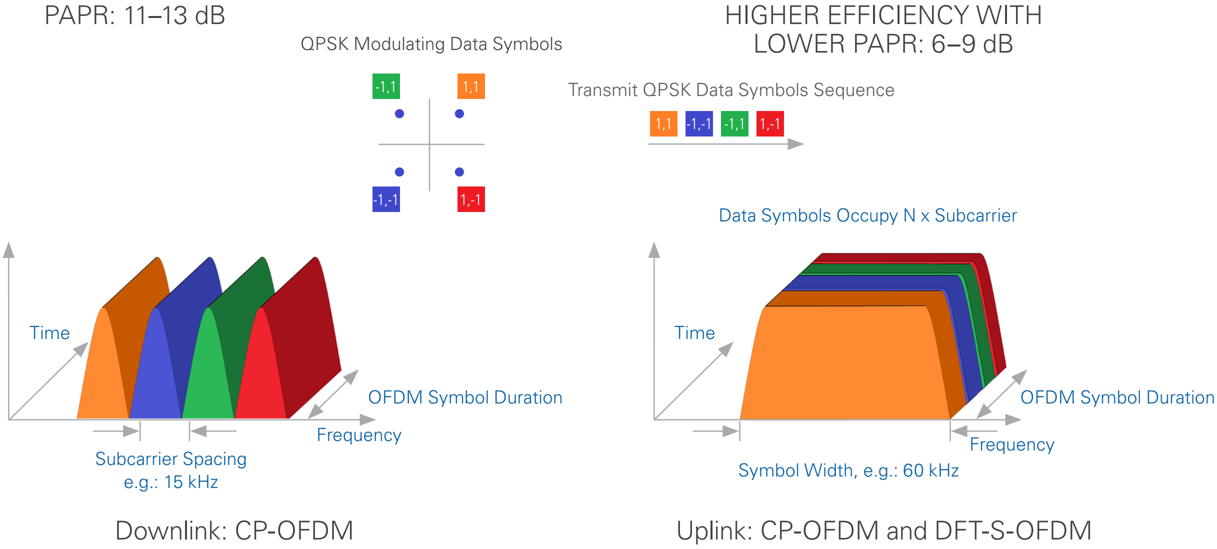


Figure 5. OFDM Versus DFT-S-OFDM

With DFT-S-OFDM, UE supports the following modulation schemes:

- Pi/2-BPSK—note that this is a new modulation scheme in NR, and it requires new IP for implementation
- 16-QAM
- 64-QAM
- 256-QAM

Flexible Subcarrier Spacing and Symbol Lengths

The 3GPP intends for NR to operate in multiple frequency bands ranging from existing cellular bands (below 1 GHz) to wider bands between 3 GHz and 5 GHz and up to the mmWave region of the spectrum. Figure 6 illustrates the current bands defined for NR operation above 6 GHz.

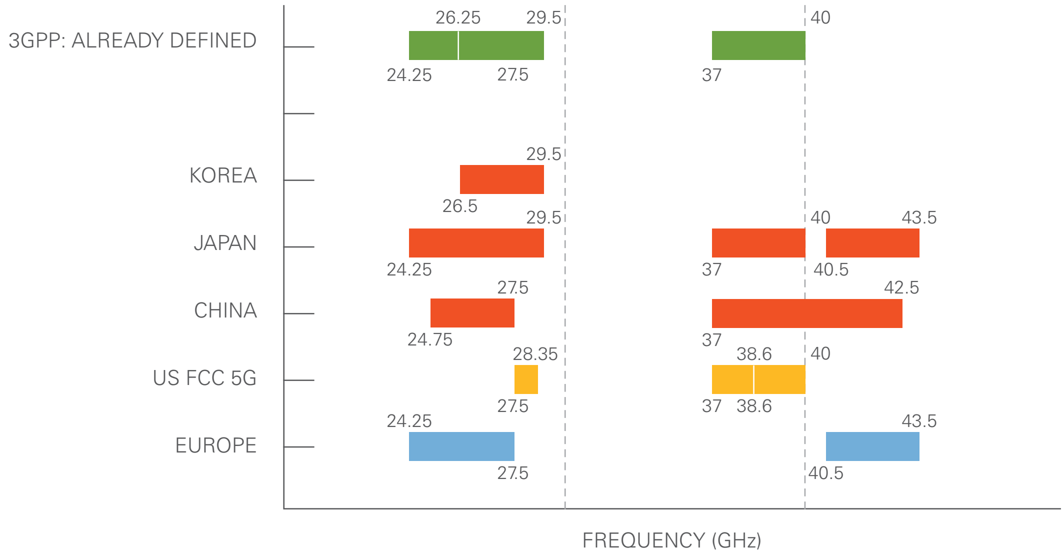


Figure 6. 3GPP-Defined and Locally Adopted Bands for NR in the Millimeter Wave Portion of the Spectrum

As the carrier frequency increases, so does the system phase noise. For example, in the carrier phase noise plot of Figure 7, the difference in phase noise between a carrier at 1 GHz and 28 GHz is about 20 dB. This phase noise increase makes it difficult for a receiver to demodulate OFDM waveforms with the narrow, fixed SCS and symbol duration of LTE at mmWave frequencies.

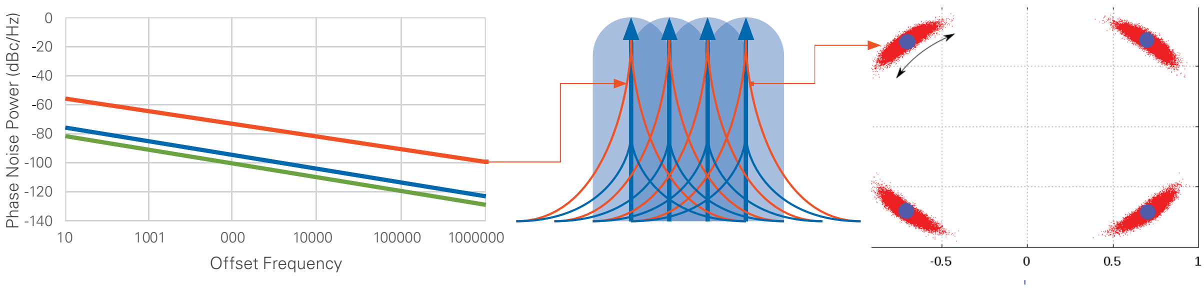


Figure 7. Effect of Phase Noise on Error Vector Magnitude

Additionally, the Doppler shift increases with carrier frequency, as shown in Figure 8. For example, UE traveling at a speed of 60 km/h using a carrier frequency of 28 GHz sees a Doppler shift of close to 1500 Hz, or 10 percent of a 15 kHz SCS. Because the channel coherence time, or the time when the system can assume that the radio channel remains constant, is approximately inversely proportional to the Doppler shift, it decreases as mobility increases. Therefore, at higher carrier frequencies and higher speeds, the system has less time to measure the channel and finish a single slot transmission.

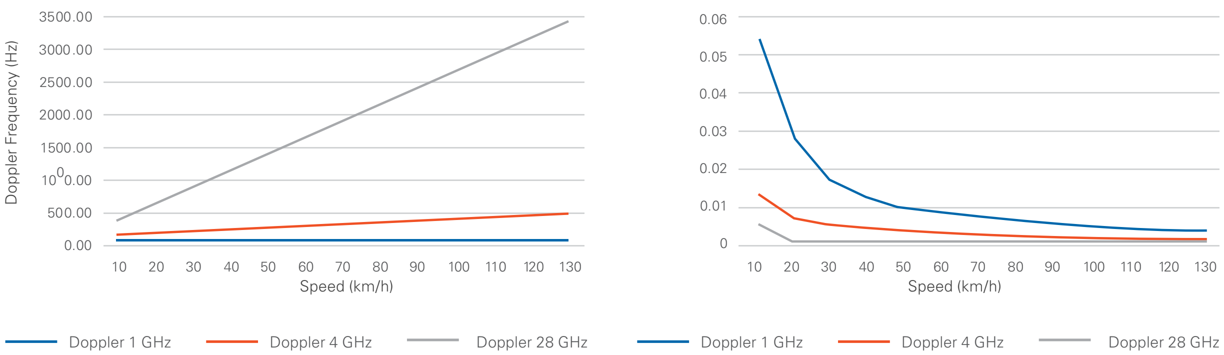


Figure 8. Doppler Shift and Channel Coherence

Also, phase noise and Doppler shift define the requirements for SCS to meet specific error vector magnitude (EVM) criteria. That means using narrow SCS causes higher EVM because of phase noise unless system designers implement the design with a high-quality local oscillator at a high cost. Also, when SCS is small, the system performance can suffer because of Doppler shift in high-mobility scenarios. On the other hand, selecting a large SCS results in excessive channel bandwidth. Furthermore, given that SCS is inversely proportional to the OFDM symbol duration, the OFDM symbol and CP length shortens as SCS increases and makes the system more susceptible to delay spread. Therefore, SCS should be as small as possible while providing enough performance in the presence of phase noise and Doppler for a desired channel bandwidth.

In the context of cellular standards, "numerology" refers to the physical layer SCS and symbol length. The 3GPP standardized on a flexible numerology that scales the space between orthogonal subcarriers, starting with the 15 kHz SCS of LTE. One of the fundamental reasons for leveraging the exhaustive work already completed for LTE numerology was the ability of NR deployments to coexist and be time-aligned with LTE networks during the first phases of deployment. This gives LTE users a gradual path to adoption of the new technology.

The NR numerology scales according to the following formula[1,2]:

$$SCS = 15 \cdot 2^{\mu}\, kHz, \mu \in \{0, 1, 2, 3, 4\}$$

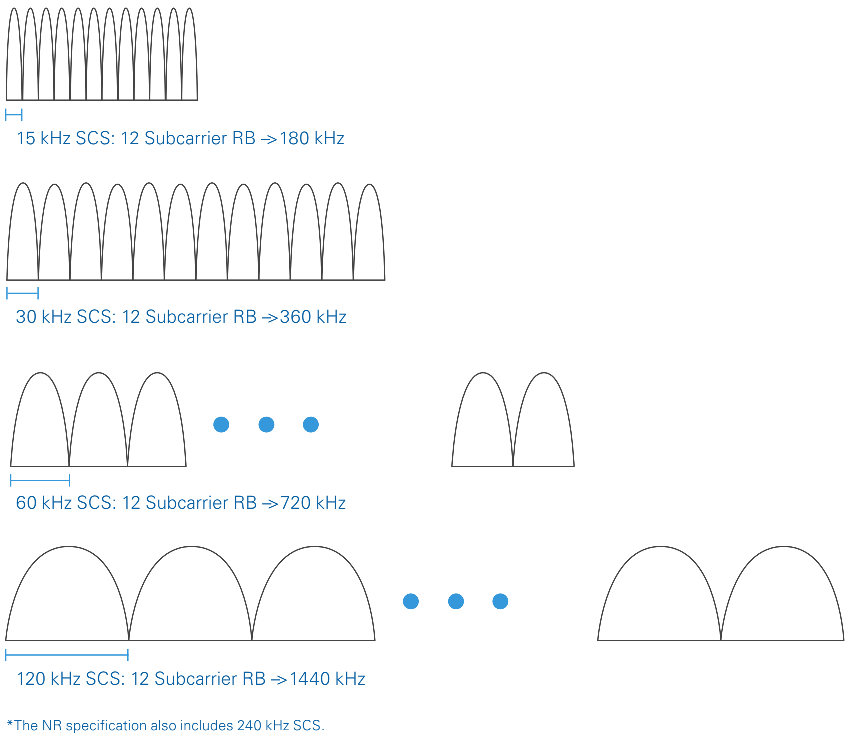


Figure 9. Flexible SCS

The standard specifies that the smallest allocatable frequency unit consists of 12 subcarriers, designated as a physical resource block (PRB). Consequently, the smaller the SCS, the narrower the PRB, as shown in Figure 9.

Figure 10 illustrates the NR channel PRBs and guard bands.

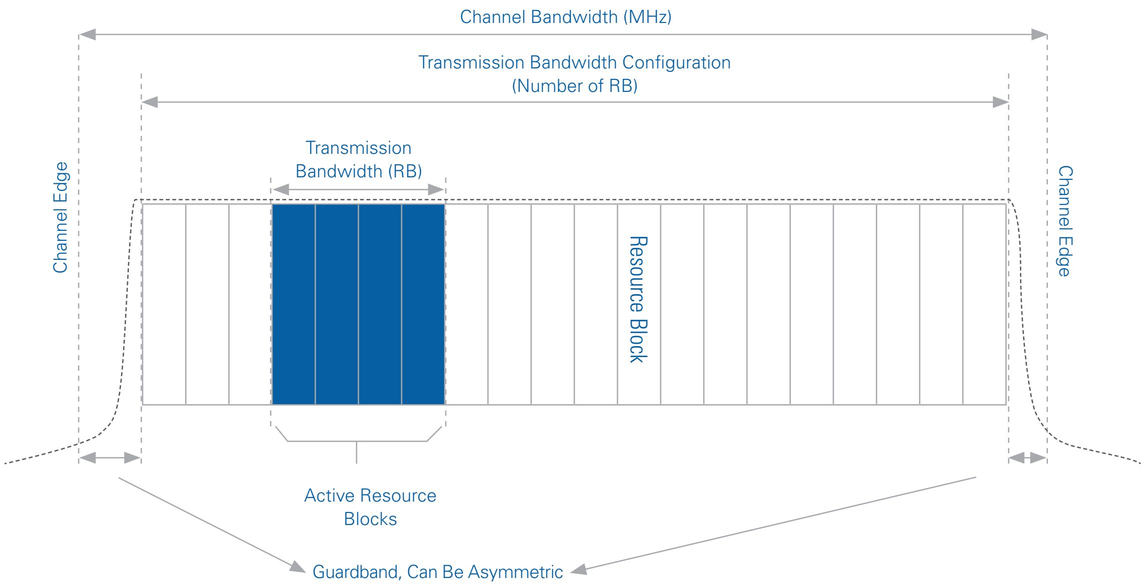


Figure 10. NR Channel Divided Into Resource Blocks

A More Scalable and Flexible Frame Structure

Along with flexible SCS, 5G NR implements a flexible frame structure that ensures 5G forward compatibility. It also minimizes design trade-offs for supporting key features like low latency, coexistence with LTE, variable length transmissions, and TDD and FDD operation in licensed and unlicensed spectra.

Slot Configurations Scale With SCS

NR slots have 14 OFDM symbols. A special case for 60 kHz SCS can have an extended CP and 12 OFDM symbols. Since OFDM symbol duration has an inversely proportional relationship with SCS, the duration of the slots scales down as SCS increases. Figure 11 shows the standard NR slot configurations.

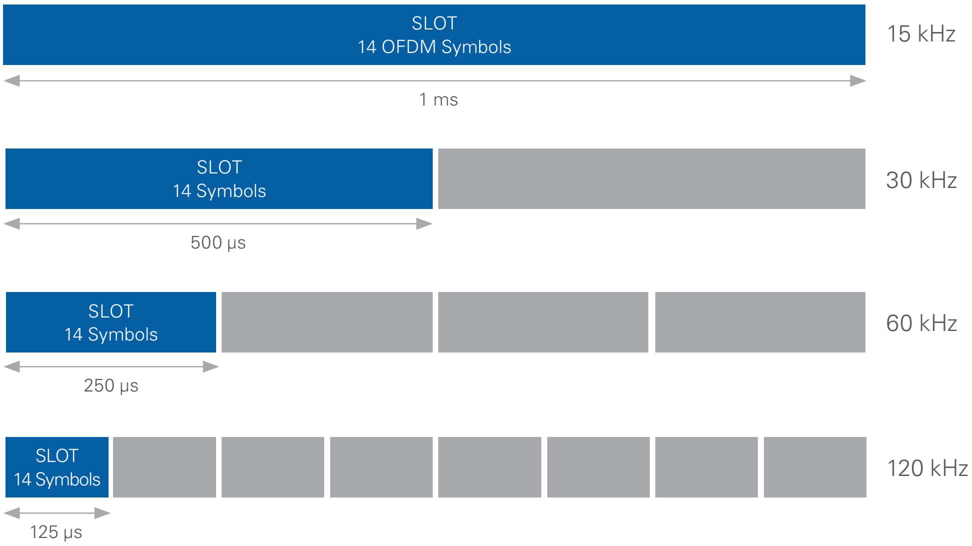


Figure 11. TDD Slot-Based Scheduling

The frame structure numbers the slots and groups them into subframes of 1 ms duration. Ten 1 ms subframes form a complete NR frame. The number of slots within a frame also varies with the choice of numerology, for example:

- Using 15 kHz of SCS results in a single 1 ms slot within the subframe, amounting to 10 slots per frame
- Using 30 kHz of SCS results in a subframe with two 500 µs slots within the subframe, amounting to 20 slots per frame

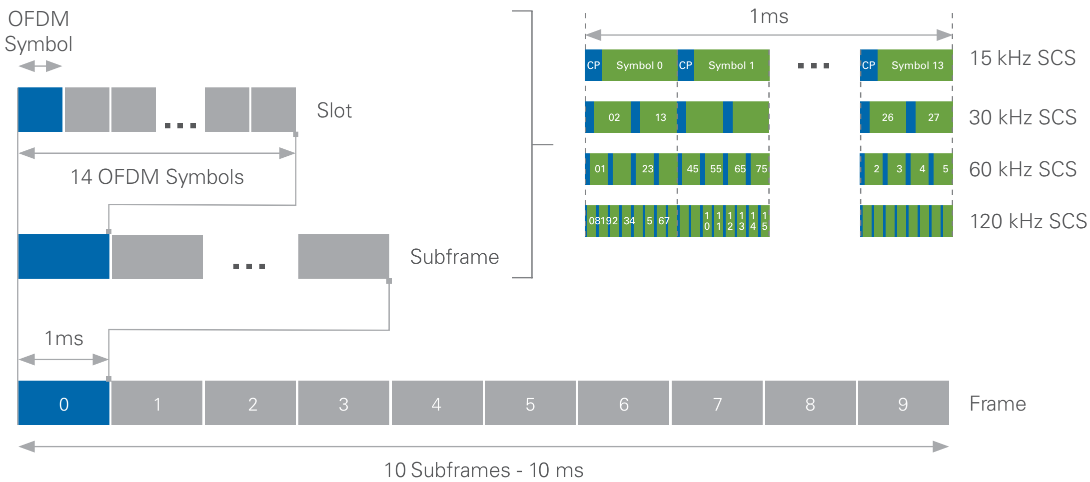


Figure 12. NR Frame Structure

The time and frequency resource structure defines the NR resource grid in Figure 13. Depending on SCS, the resource grid changes as the number of available subcarriers and OFDM symbols change. That is, for each numerology and carrier, NR specifies a resource grid with a width given by the maximum number of resource blocks per SCS multiplied by the number of subcarriers per resource block, and a length given by the number of OFDM symbols per subframe.

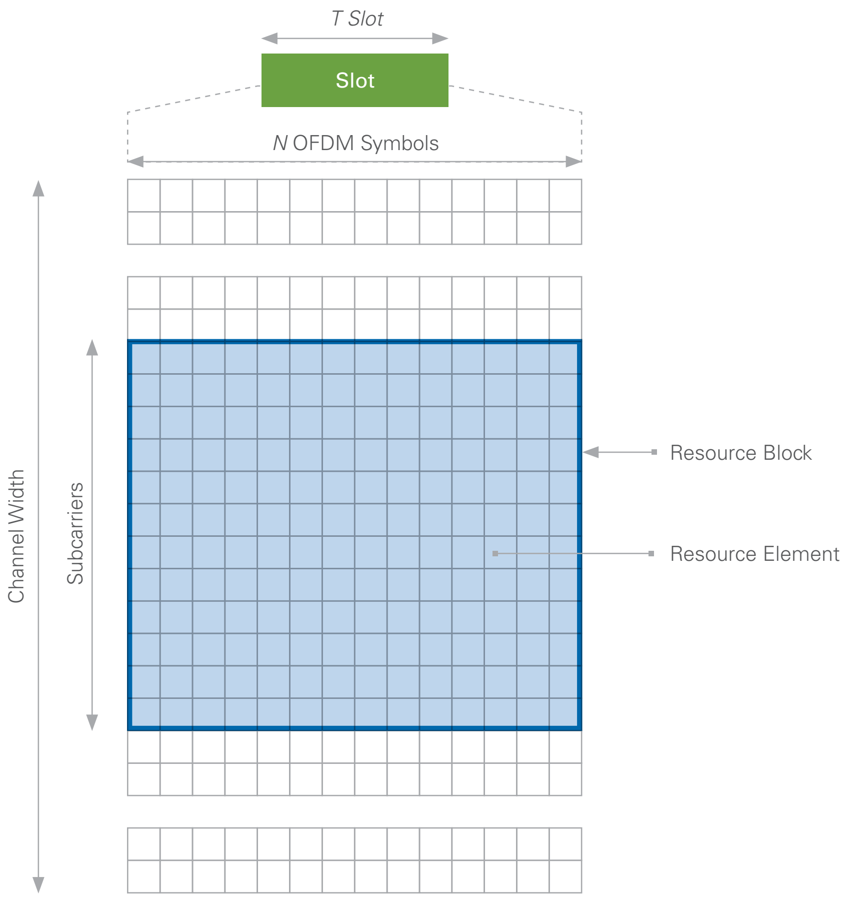


Figure 13. NR Resource Grid

To support agile and efficient use of TDD resources, NR also implements a flexible slot structure. The system can allocate a slot as all DL, all UL, or a mix of DL and UL to service asymmetric traffic, as Figure 14 illustrates. DL control takes place at the beginning of the slot and UL control at the end. The system can either configure the mixed DL/UL slot statically, as in an LTE DL/UL TDD configuration, or change the allocation of the DL/UL mix dynamically for better efficiency and scheduling based on traffic needs.

To accomplish this, the NR standard includes the slot format indicator (SFI), a field that informs a user whether an OFDM symbol contains DL, UL, or flexible (either DL or UL) slots. The SFI indicates the link direction for one or many slots by indexing a row of the UE's preconfigured table of possible link direction assignments.

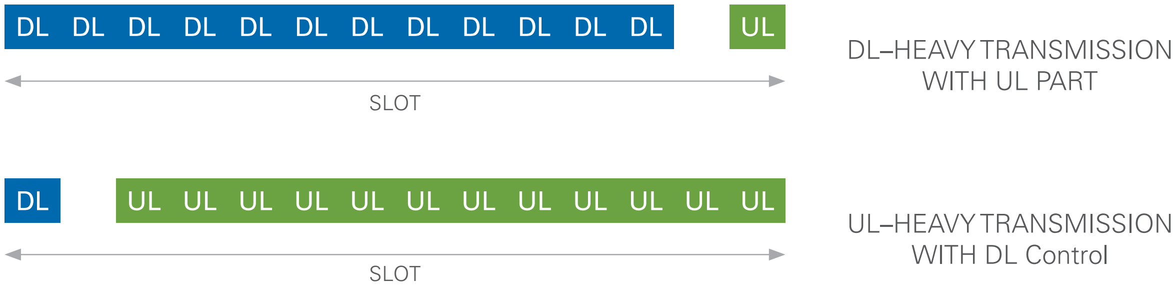


Figure 14. Flexible Slot Structure for Managing TDD Resources Dynamically

Furthermore, when the system needs to work with large payloads that don't demand the most immediate attention, the standard allows for slot aggregation. In the case of eMBB, for example, having aggregated slots and longer transmission times meets application requirements while reducing TDD switching and signaling overhead.

Minislots Enable Even Further Dynamic Scheduling

The NR standard is also considering the use of "minislots" to support bursty, asynchronous transmissions with variable start positions and durations shorter than the typical, 14-symbol slot. A minislot represents the smallest possible scheduling unit, and it can last for 7, 4, or 2 OFDM symbols. Minislots are especially important for enabling low-latency transmissions.

Imagine the future case of a mission-critical system (URLLC) that needs to communicate its information with minimal latency, so the standard 10 ms frame is too long. The NR numerology allows minislots to "puncture" an existing frame without waiting for the system to schedule it. To avoid collisions, the network detects a minislot burst and manages the URLLC device with the highest priority. Additionally, the network can schedule minislots ahead of time, which becomes increasingly relevant in a mmWave operation where the transmission of a few OFDM symbols mapped across large bandwidths might be enough to carry smaller payloads. As of December 2017, the 3GPP has not yet fully specified this feature, and it will not be part of Release 15.[3]

NR Reference Signals

To increase protocol efficiency, and to keep transmissions contained within a slot or beam without having to depend on other slots and beams, NR introduces the following four main reference signals. Unlike the LTE standard, which is constantly exchanging reference signals to manage the link, an NR transmitter sends these reference signals only when necessary.[4]

1. **Demodulation Reference Signal (DMRS)**—The DMRS is specific for specific UE, and a system uses this signal to estimate the radio channel. The system can beamform the DMRS, keep it within a scheduled resource, and transmit it only when necessary in either DL or UL. Additionally, multiple orthogonal DMRSs can be allocated to support MIMO transmission. The network presents users with DMRS information early on for the initial decoding requirement that low-latency applications need, but it only occasionally presents this information for low-speed scenarios in which the channel shows little change. Alternatively, tracking fast changes in high-mobility scenarios might increase the rate of transmission (called "additional DMRS").

2. **Phase Tracking Reference Signal (PTRS)**—As mentioned before, the phase noise of the transmitters increases as the frequency of operation increases. The PTRS plays a crucial role especially at mmWave frequencies to minimize the effect of the oscillator phase noise on system performance. One of the main problems that phase noise introduces into an

OFDM signal appears as a common phase rotation of all the subcarriers, known as common phase error (CPE). The NR system typically maps the PTRS information to a few subcarriers per symbol because the phase rotation affects all subcarriers within an OFDM symbol equally but shows low correlation from symbol to symbol. The system configures the PTRS depending on the quality of the oscillators, carrier frequency, SCS, and modulation and coding schemes that the transmission uses.

3. **Sounding Reference Signal (SRS)**—As a UL-only signal, the SRS is transmitted by the UE to help the system obtain the channel state information (CSI) for each user. This information describes how the NR signal propagates from the transmitter to the receiver and represents the combined effect of scattering, fading, and power decay with distance, for example. The system uses the SRS for resource scheduling, link adaptation, Massive MIMO, and beam management.
4. **Channel State Information Reference Signal (CSI-RS)**—As a DL-only signal, the CSI-RS the UE receives is used to estimate the channel and report channel quality information back to the gNB. During MIMO operations, NR uses different antenna approaches based on the carrier frequency. At lower frequencies, the system uses a modest number of active antennas for MU-MIMO and adds FDD operations. In this case, the UE needs the CSI-RS to calculate the CSI and report it back in the UL direction.

MIMO

With the goal of using the spectrum more efficiently and serving more users, NR plans to take full advantage of MU-MIMO technology. MU-MIMO adds multiple access (multiuser) capabilities to MIMO by exploiting the distributed and uncorrelated spatial location of those multiple users. In this configuration, the gNB sends the CSI-RS to UE in the coverage area, and based on the SRS response of each UE device, the gNB computes the spatial location of each receiver. The streams of data destined for each receiver go through a precoding matrix (W-Matrix), where the data symbols get combined into signals streaming to each of the elements of the gNB's antenna array[5] (see Figure 15.)

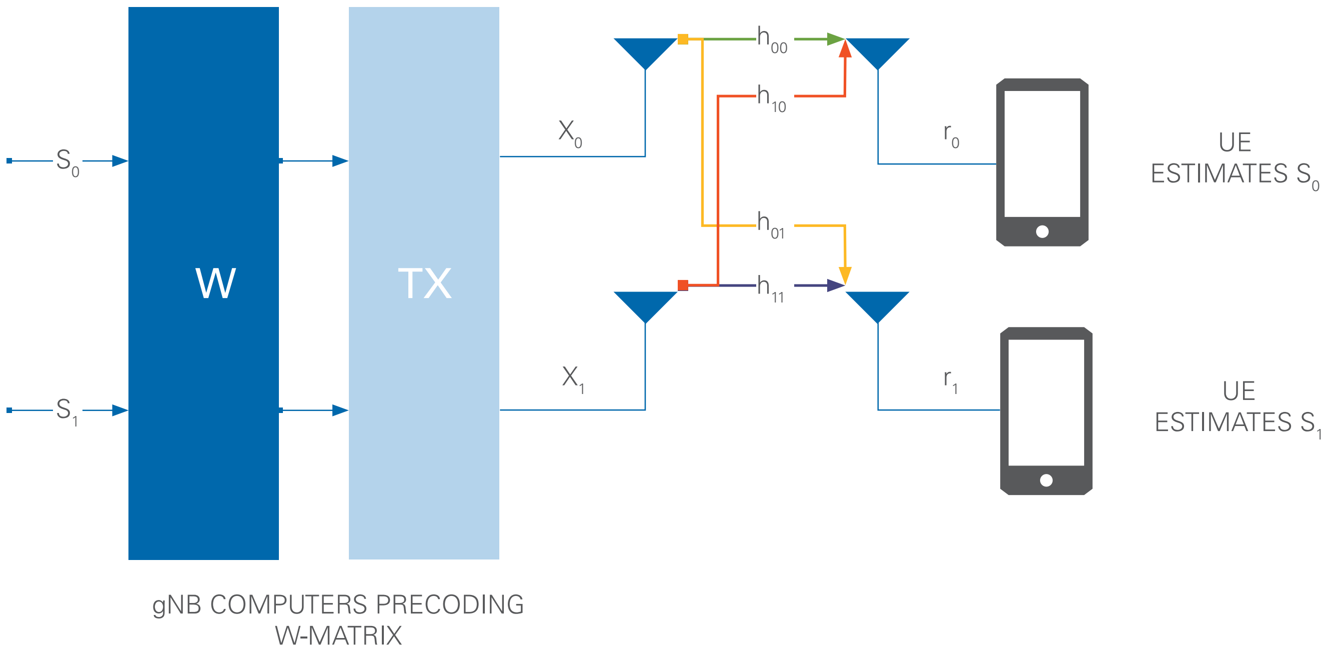


Figure 15. Representation of MU-MIMO on the DL

The multiple data streams have their own independent and appropriate weightings that apply different phase offsets to each stream so that the waveforms interfere constructively and arrive in phase at each receiver. This maximizes the signal strength at each user's location while presenting minimum signal strength (a null) in the directions of the other receivers, as Figure 16 shows.

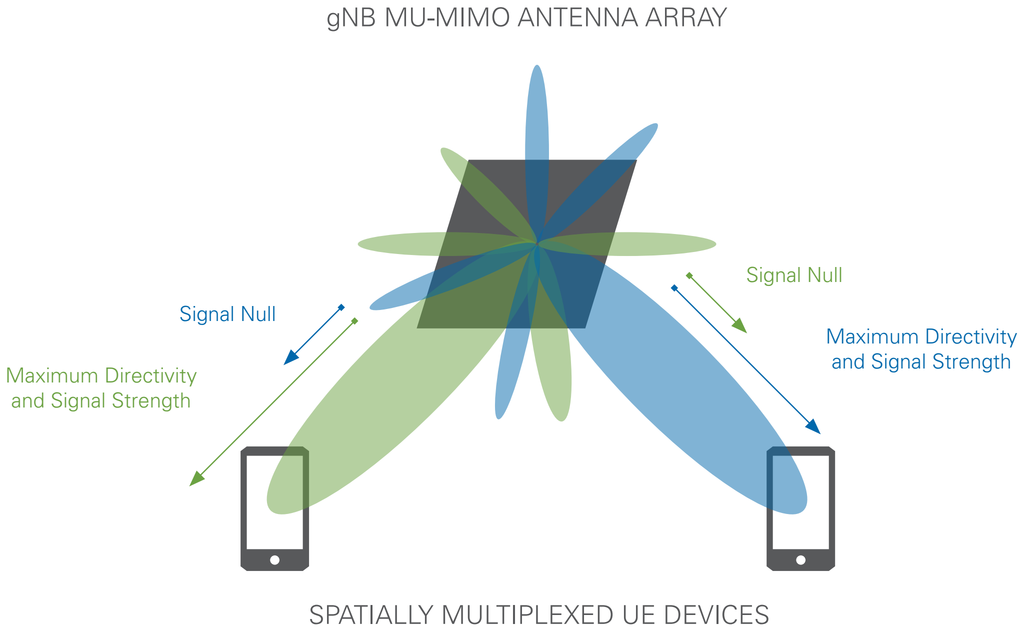


Figure 16. MIMO Beamforming for Spatial Multiplexing

Consequently, the gNB talks to multiple UE devices independently and simultaneously, effectively multiplexing them in space. As an additional benefit, in this MU-MIMO implementation, the UE devices don't need any knowledge of the channel or additional processing to get their data streams.

MU-MIMO on the DL boosts the NR system's capacity. It scales with the minimum of the number of gNB antennas and the sum of the number of UE devices multiplied by the number of antennas per UE device. In other words, MU-MIMO can achieve MIMO capacity gains with gNB antenna arrays and much simpler single-antenna UE devices.

Massive MIMO for 5G

Taking the MIMO approach a step further, a Massive MIMO configuration is implemented when a system has many times more gNB antennas than the number of UE devices per signaling resource. The large number of gNB antennas relative to the number of UE devices can yield huge gains in spectral efficiency. Such conditions enable the system to serve many more devices simultaneously within the same frequency band compared with today's 4G systems (see Figure 17). NI, along with industry leaders such as Samsung, continues to demonstrate the viability of Massive MIMO systems through its platform of software defined radio and flexible software for rapid wireless prototyping.

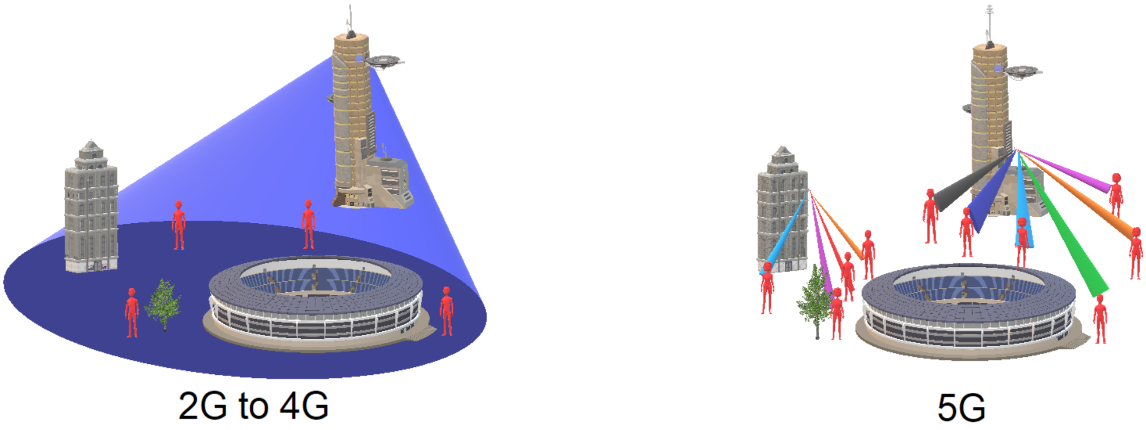


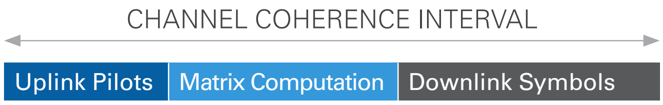
Figure 17. Multiantenna Array for Massive MIMO

Currently, the strongest case for Massive MIMO operation is at frequencies below 6 GHz. Spectrum is scarce and valuable in this region. In these bands, Massive MIMO systems can achieve significant spectral efficiency by spatially multiplexing many terminals. The system can also achieve superior energy efficiency by exploiting large antenna array gains to lower the amount of power that each front end must handle.

In Massive MIMO systems, each antenna has its own RF and digital baseband chain. The gNB maintains tight phase control and processes the signals from all antennas. The system can gain a fuller picture of the channel response on the UL and respond quickly to changes in the channel using digital processing. Massive MIMO operates mainly in TDD, which permits the assumption of channel reciprocity. That enables the system to estimate DL channels from UL pilots and eliminates the need for prior knowledge of the channel.

Another advantage of future Massive MIMO systems is that they'll provide better and more consistent service to all UE in a coverage area. Because of an improved link budget and the ability to place target UE precisely within the radiated beam while nulling nontarget UE (spatial resolution), power control algorithms can achieve greater fairness among the UE.

User mobility can limit how well Massive MIMO solutions scale up in performance. For proper channel estimation, the system needs to send UL pilots and payload in the UL direction. The faster UE moves, the shorter the channel coherence time. For example, in large coverage areas with fast UE, such as a car traveling at 120 km/h on a highway, the channel's coherence time at 2 GHz carrier frequency drops to around 1 ms. This requires the system to recalculate the channel 1000 times per second to track the UE as it moves and limit the multiplexing gain to a smaller number of terminals. Figure 18 shows how coherence time scales with both carrier frequency and UE speed. Conversely, in more controlled environments with little or no mobility such as fixed wireless access, the system can accommodate hundreds of terminals through spatial multiplexing using narrow beams.



Frequency	3 km/h	30 km/h	120 km/h	500 km/h
2 GHz	45 ms	4.5 ms	1.125 ms	27 µs
28 GHz	3.2 ms	320 µs	80 µs	19 µs

Limited Mobility

Figure 18. Effect of Mobility on Channel Coherence Time

mmWave for 5G

Industry and academic researchers consider available mmWave bands as the next frontier to serve the data-hungry wireless applications of the future. New 5G systems operating at 28 GHz and above offer more available spectrum for larger channels, which work well for multi-Gbps links. Although these frequencies see less spectral crowding than those below 6 GHz, they experience different propagation effects such as higher free-space path loss and atmospheric attenuation, weak indoor penetration, and poor diffraction around objects.

To overcome these undesired effects, mmWave antenna arrays can focus their beams and take advantage of the antenna array gain. Fortunately, the size of these antenna arrays decreases as the frequency of operation increases, allowing a mmWave antenna array with many elements to take up the same area that a single sub-6 GHz element occupies (Figure 19).

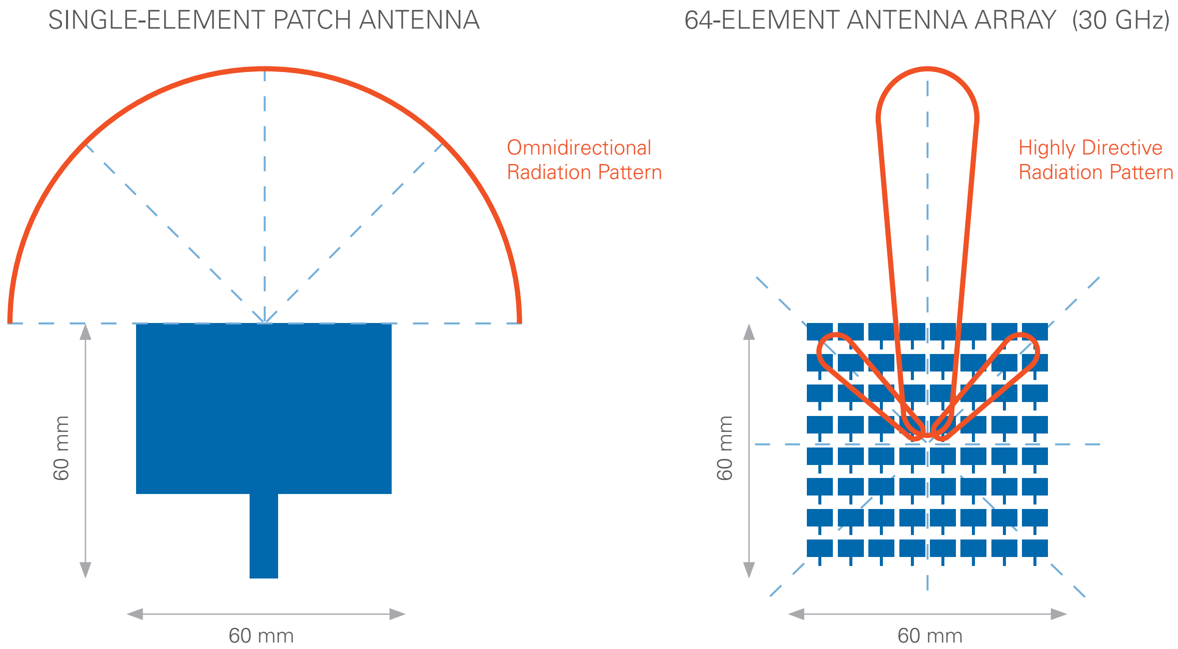


Figure 19. Comparison of mmWave and Sub-6 GHz Antenna Arrays

Analog Beam Steering to Manage Complexity

As presented above, Massive MU-MIMO systems require far more transmit RF chains than UE devices for proper spatial multiplexing. This differs from a system comprising just one RF chain that feeds many antennas, the phase of which is controlled analogically to focus and steer the radiation pattern (see Figure 20). For MU-MIMO purposes, such a system can be categorized as a single-antenna terminal that happens to have a directive, steerable antenna.

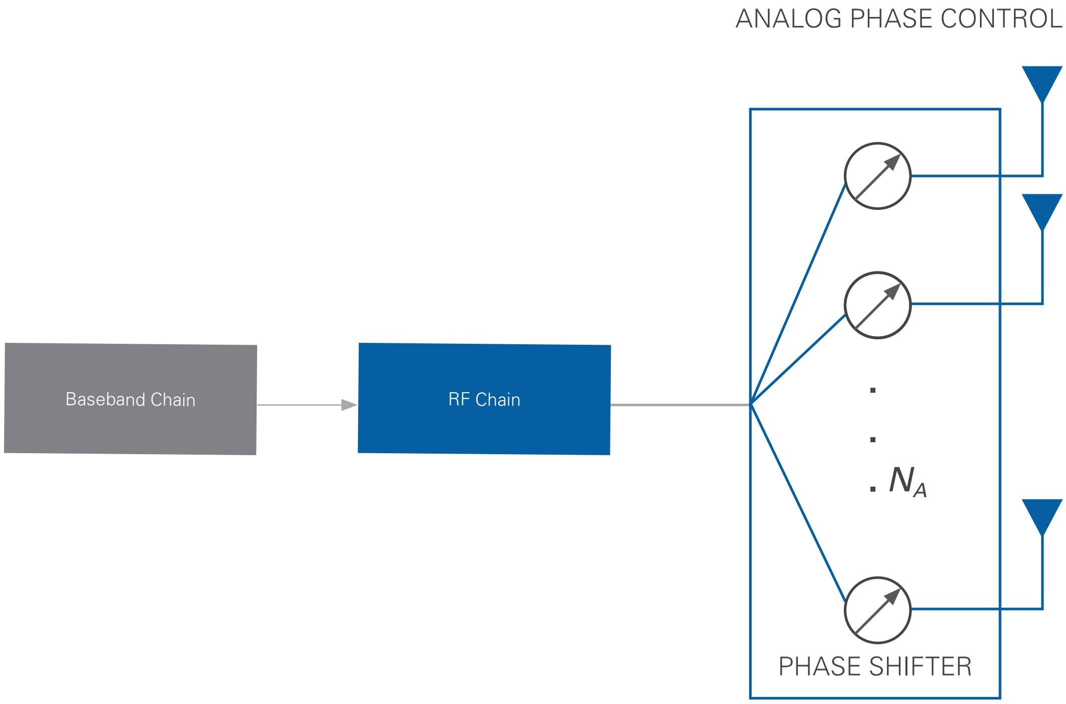


Figure 20. Single RF Chain With Analog Beam Steering

One of the main drawbacks of Massive MIMO systems is the high complexity and cost of integrating and deploying a massive number of RF chains, especially at mmWave frequencies. Researchers have proposed several hybrid (digital and analog) beamforming alternatives[6] to allow 5G gNBs to maintain a high number of antennas while keeping the MU-MIMO implementation costs down. Figure 21 illustrates a hybrid system with a common baseband processing stage that feeds multiple data streams to their corresponding RF chains. These streams undergo digital beamforming signal processing before moving on to the analog stage. At this last stage, the system applies beam steering with analog phase shifters, which focus the beam toward a specific direction. This results in spatially multiplexed RF streams contained within a directional beam.

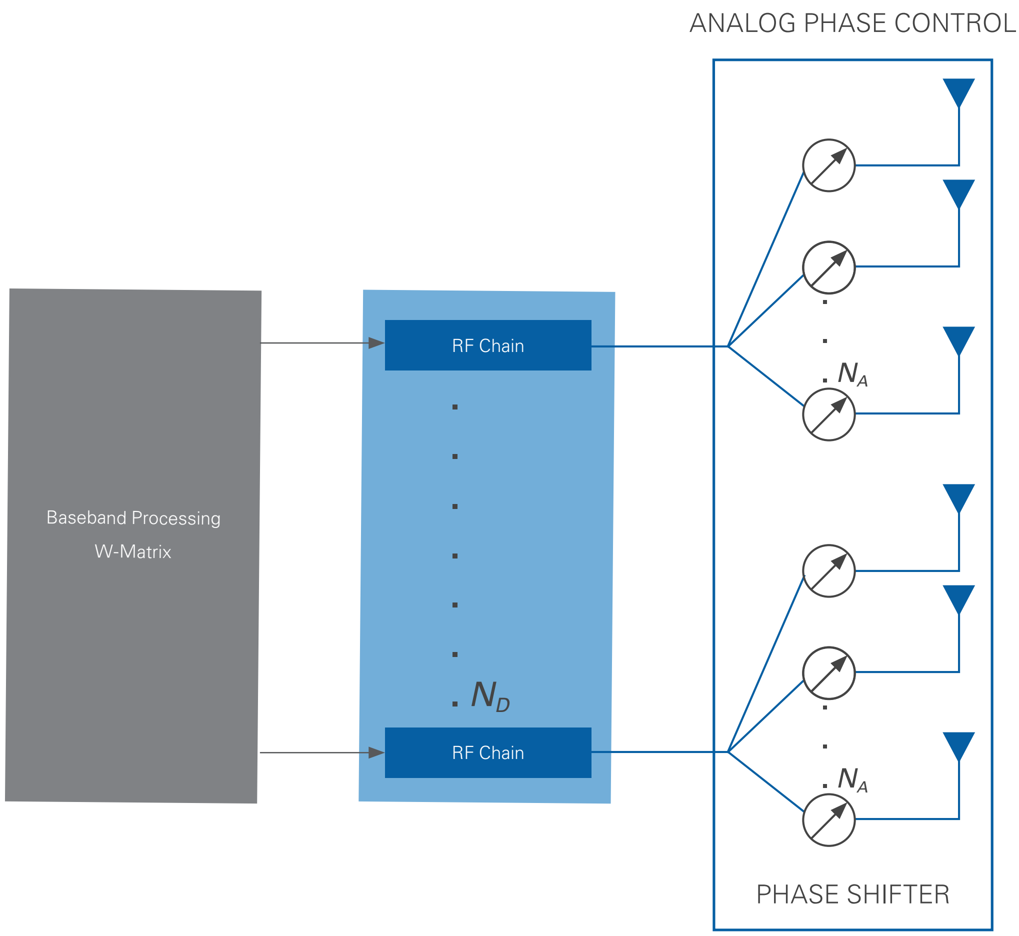


Figure 21. Hybrid Digital and Analog Beamforming

Finally, recall that the channel coherence time decreases significantly at mmWave frequencies, which places tough restrictions on mobility applications. Researchers continue to investigate new ways to improve UE mobility at mmWave frequencies, but most likely the first 5G mmWave deployments will serve fixed wireless access applications such as backhaul and sidelink.

Gaining Access and Managing Beams

Managing the large signal propagation loss at frequencies above 20 GHz is one of the main technical challenges of operating in mmWave bands. In practical terms, this loss reduces the possible cell coverage area and range. To compensate for it, the standard designers settled on beamforming technology with antenna arrays as a way of focusing the RF energy toward individual users and boosting the signal gain. However, UE can no longer rely on the mmWave gNBs to broadcast omnidirectional signals to establish the first connection.

The NR standard implements a new procedure for UE to gain initial access to the gNB. Upon arrival to a new cell coverage area, UE is blind to the location of the beam, ignoring the direction in which the gNB is currently transmitting to begin the network access procedure.

The NR initial access procedure presents an elegant solution for UE to establish communication with the gNB. It solves the problem of finding the gNB in the dark not only for mmWave operation but also for sub-6 GHz omnidirectional operation. This means that the initial access procedure must work in single-beam and multibeam scenarios. It also must support NR and LTE coexistence.

The procedure follows the steps depicted in Figure 22.

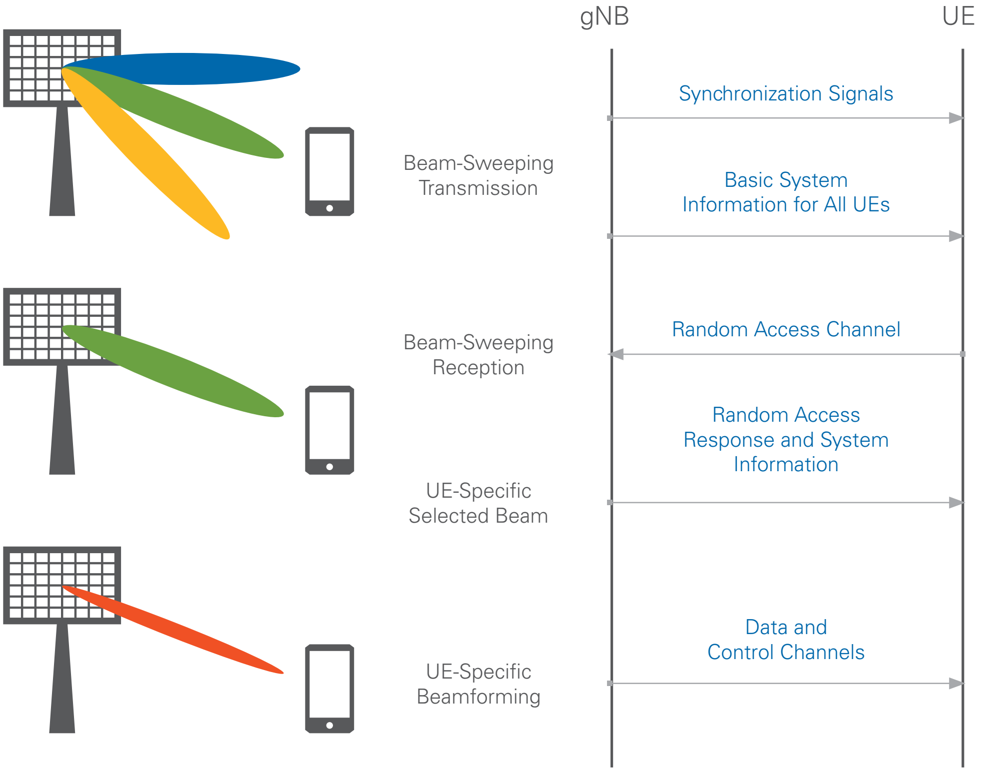


Figure 22. Initial Access Procedure

1. **Beam-sweeping transmission**—The gNB transmits the physical broadcast channel (PBCH) in groups of four OFDM symbols called synchronization signal blocks (SS blocks) sequentially in multiple directions, as depicted by the blue, green, and yellow beams, and maps each one to a different spatial direction. Using the concept of beam sweeping, the gNB transmits both the synchronization signals and the system configuration information that the UE needs to access the network.
2. **Beam-sweeping reception**—The UE detects the best SS block (strongest detected beam) by listening until it matches the beam direction of the transmitter. This allows the UE to decode the best SS block and extract its time index. Knowing when the gNB will use that beam direction again, the UE transmits to the gNB on the physical random access channel (PRACH) at the right time. The gNB now knows in which direction and at what time the UE will transmit UL information.
3. **UE-specific selected beam**—Once the UE and gNB establish communication on the best beam, the gNB sends the rest of the system information that the UE needs to set up a connection with the gNB.
4. **UE-specific beamforming**—At this point, the system can switch from general, wider beam coverage to UE-specific coverage with a narrower beam using beam-refining procedures.

Bandwidth Parts

In future 5G applications, a large range of devices and equipment will have to operate successfully across many different bands with varied spectrum availability. An example is UE with limited RF bandwidth needing to operate alongside a more powerful device that can fill a whole channel using carrier aggregation and a third device that can cover the whole channel with a single RF chain[7] (Figure 23).

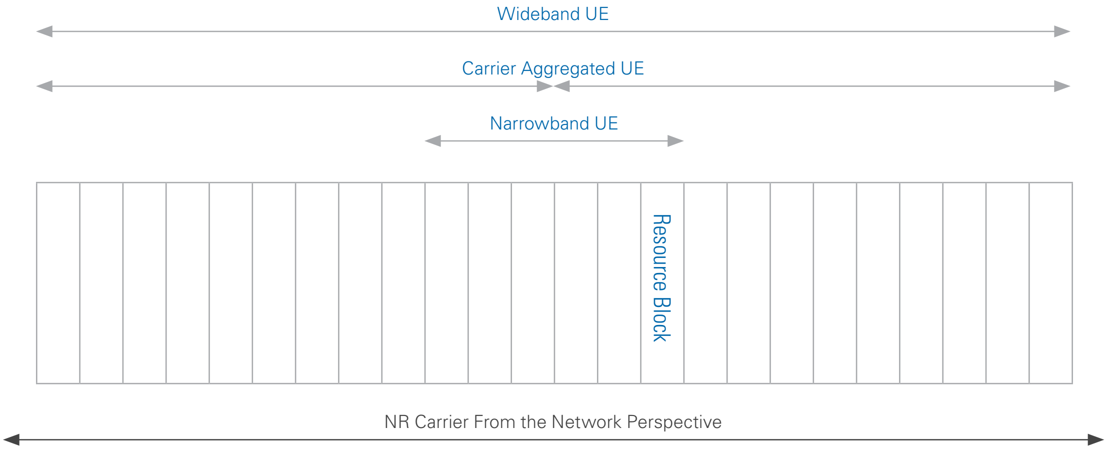


Figure 23. Parts to Manage the Spectrum More Efficiently

Though wide bandwidth operation has a direct effect on the data rates that users can experience, it comes at a cost. When UE doesn't need high data rates, wide bandwidth leads to inefficient use of RF and baseband processing resources.

To address this, the 3GPP developed the new concept of bandwidth parts (BWPs): the network configures certain UE with one wideband carrier and separately configures other UE with a set of intraband contiguous component carriers using carrier aggregation. This allows for a greater diversity of devices with varying capabilities to share the same wideband carrier. This kind of flexible network operation that adjusts to UE's differing RF capability does not exist in LTE.

A BWP consists of a group of contiguous PRBs. Each BWP has an associated SCS and CP (numerology). As a result, the system can use the BWP to reconfigure UE with a certain numerology. UE starts out with a default active BWP during the initial access until the system configures the UE's BWPs explicitly during or after connection establishment. Figure 25 shows that the network is allocating two BWPs (BWP 1 and 2) to one UE device while reserving a third, full-channel, overlapping BWP (BWP 3) for potential use by another higher bandwidth UE device or application.

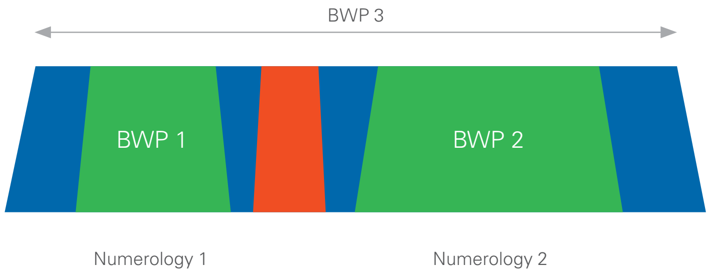


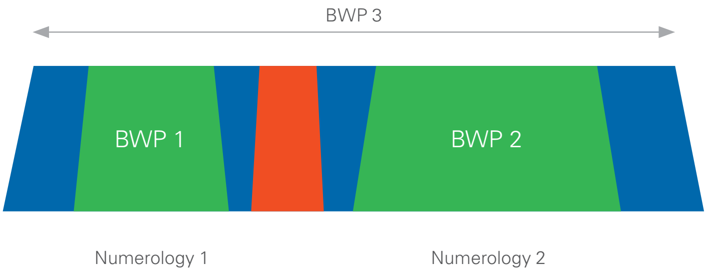
Figure 24. Bandwidth Parts

The system can configure DL and UL BWPs for each serving cell separately and independently. In Release 15, only one BWP in DL and one in UL are active at any point in time, but the UE can have up to four configured BWPs.

To summarize, NR will have the flexibility to serve many different use cases effectively by using BWPs, for example:

Supporting UE that has narrow RF capabilities and reducing energy consumption when a device doesn't require full bandwidth operation

Supporting multiple numerologies and allowing operation in noncontiguous spectrum



Enabling forward compatibility with devices and applications that the market will define in the future

Figure 25. NR Serving Many Use Cases With BWPs

Conclusion: Comparing LTE and 5G NR PHY

Now compare the fundamental technical features of 5G NR with those of current LTE implementations.

Better Spectrum Utilization

Wideband 5G carriers are planned to occupy up to 98 percent of the channel, avoiding large guard bands between carriers. This helps reduce channel overhead and allows for faster load balancing than LTE aggregated carriers can implement. For example, Figure 27 compares five 20 MHz aggregated LTE carriers versus a proposed single 98 MHz 5G NR carrier.

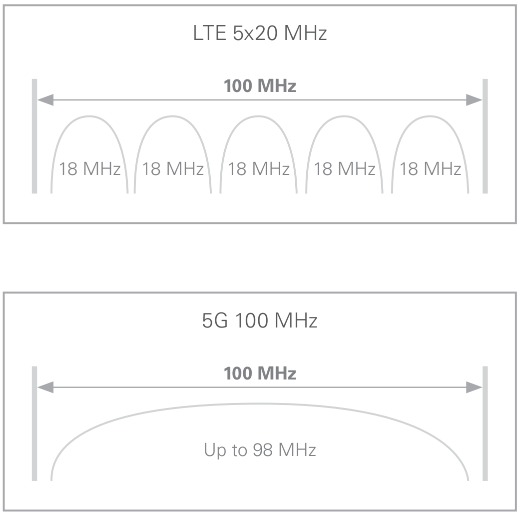


Figure 26. Improved Channel Utilization With Wideband 5G Carriers

Flexible Numerology and Frame Structure

LTE uses fixed 15 kHz SCS with a maximum of 1200 subcarriers in a 20 MHz channel. In contrast, NR allows for greater spectrum utilization with channels of various sizes, variable SCS and slot length, and a maximum of 3300 subcarriers per channel.

Enhanced Efficiency With Leaner Signaling

Unlike LTE, which transmits cell-specific reference signals four times per millisecond, synchronizes every 5 ms, and broadcasts every 10 ms, 5G has no cell-specific reference signals and synchronizes and broadcasts every 20 ms. This enables greater base station power savings.

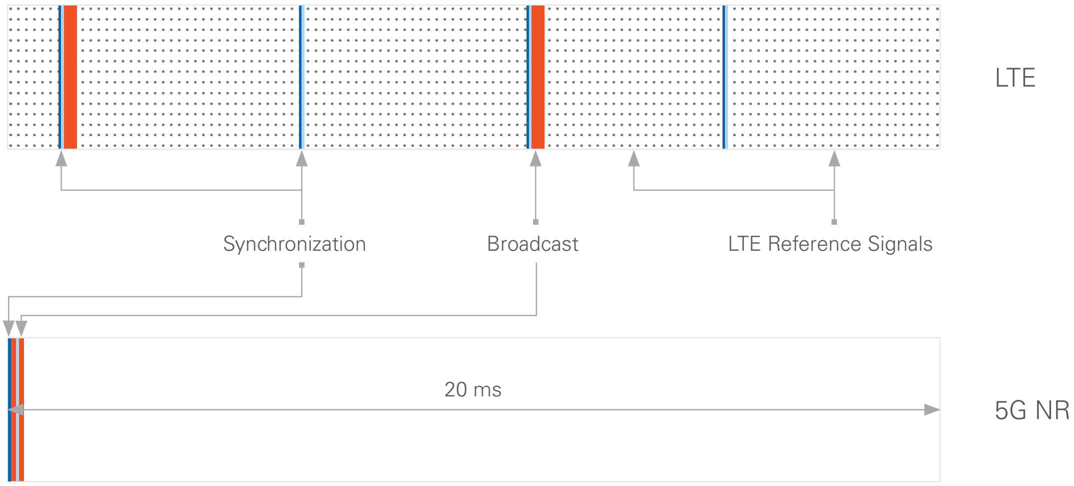


Figure 27. Signaling Efficiency in LTE Versus 5G NR

Manage TDD Resources Dynamically

LTE has a fixed, static TDD structure that allocates slots to either DL, UL, or synchronization and control signals. That is, within a radio frame, LTE TDD switches multiple times between DL and UL transmission and vice versa. On the other hand, within a slot, 5G can change dynamically between DL and UL to handle traffic demands in either direction.

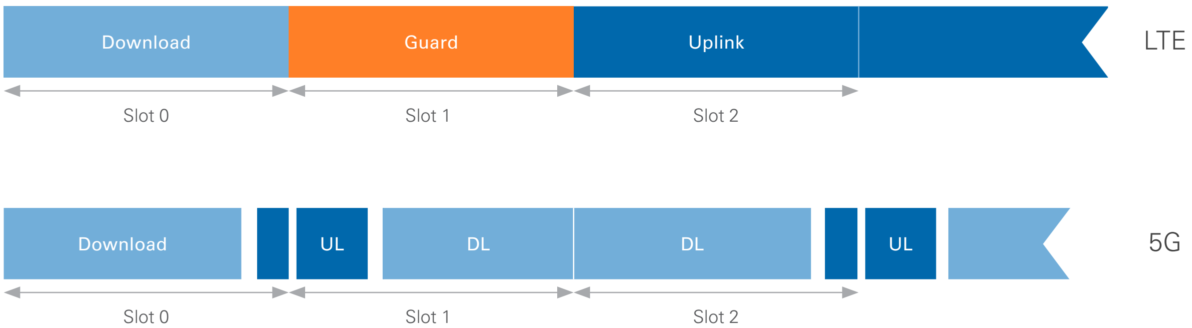


Figure 28. NR Manages TDD Resources More Dynamically

Operation at mmWave Frequencies With Wider Channels

Today's licensed LTE networks are limited to operating at a maximum frequency of around 3800 MHz. The 5G NR networks will take advantage of both existing cellular bands and wide channels in newly licensed spectrum around 30 and 40 GHz.

The specification of higher bandwidth channels and multiple numerology options will enable NR systems to operate in sub-6 GHz bands and mmWave bands with appropriate handling of multipath delay spread, channel coherence time, and phase noise. Furthermore, NR will support existing and new services with even higher data rates and address different latency and mobility requirements by changing the transmission turnaround time using variable SCS and by allocating wide channels around and above 28 GHz. NR will use the latest developments in Massive MIMO and beamforming technology to maximize spectral efficiency and guarantee better service for a larger number of users.

Additionally, considering the commercial practicalities of deploying different UE with different RF capabilities, the new BWP concept in NR will lead to more energy-efficient UE operation and superior spectrum management.

In conclusion, 5G wireless technology promises to deliver an abundance of reliable, data-rich, and highly connected applications for more of the world's population. Although deploying an infrastructure that can support this and creating the next generation of 5G devices present significant design and test challenges, NI's platform-based approach to designing, prototyping, and testing wireless technologies will be key in making 5G a reality within the next decade.

Glossary

3GPP	Third Generation Partnership Project
AR	augmented reality
BCH	broadcast channel
BPSK	binary phase-shift keying
BS	base station
BWP	bandwidth parts
CP	cyclic prefix
CP-OFDM	cyclic prefix orthogonal frequency division multiplexing
CSI-RS	Channel State Information Reference Signal
DFT	discrete Fourier transform
DFT-SOFDM	discrete Fourier transform spread orthogonal frequency division multiplexing
DL	downlink
DMRS	demodulation reference signal
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
EVM	error vector magnitude
FDD	frequency division duplex
FDMA	frequency division multiple access
FFT	fast Fourier transform
GP	guard period

gNB	g node b, a 5G base station
mMTC	Massive Machine-Type Communication
mmWave	millimeter wave
MIMO	multiple input, multiple output
MU-MIMO	Multiuser MIMO
NR	New Radio
OFDM	orthogonal frequency division multiplexing
PA	power amplifier
PAPR	peak-to-average power ratio
PBCH	physical broadcast channel
PRACH	Physical Random Access Channel
PRB	physical resource block
PTRS	phase-tracking reference signal
QAM	quadrature amplitude modulation
QPSK	quadrature (quaternary) phase-shift keying
RAN	radio access network
SCS	subcarrier spacing
SRS	Sounding Reference Signal
TDD	time division duplex(ing)
TDM	time division multiplexing
UE	user equipment
UL	uplink (reverse link)
URLLC	Ultra-Reliable Low-Latency Communication
VR	virtual reality

Endnotes

[1] 3GPP TS 38.101-1 V15.0.0 (2017-12) Technical Specification Radio Access Network; NR; User Equipment (UE) radio transmission and reception.

[2] 3GPP TS 38.211 V15.0.0 (2017-12) Technical Specification Radio Access Network; NR; Physical channels and modulation.

[3] 3GPP TR 38.912 V14.1.0 Technical Specification Group Radio Access Network; Study on New Radio (NR) access technology (Release 14.)

[4] 3GPP TS 38.214 V15.0.0 (2017-12) Technical Specification Radio Access Network; NR; Physical layer procedures for data.

[5] Q. H. Spencer, C. B. Peel, A. L. Swindlehurst, and M. Haardt, "An introduction to the multi-user MIMO downlink," in *IEEE Communications Magazine*, vol. 42, no. 10, pp. 60—67, Oct. 2004.

[6] S. Han, C. I. I, Z. Xu, and C. Rowell, "Large-scale antenna systems with hybrid analog and digital beamforming for millimeter wave 5G," in *IEEE Communications Magazine*, vol. 53, no. 1, pp. 186–194, January 2015.

[7] 3GPP TS 38.213 V15.0.0 (2017-12) Technical Specification Radio Access Network; NR; Physical layer procedures for control.