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New Radio for 5G

The future of mobile broadband

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New Radio (NR) is a study item in the 3rd Generation Partnership Project Radio Access Network Working Group (3GPP RAN-WG) focusing on a new Radio Access Technology (RAT) for the 5th Generation (5G) cellular communications systems. Together with the next generation core network (NextGen Core), NR fulfills requirements set forth by the International Mobile Telecommunications (IMT)-2020 in the International Telecommunication Union (ITU). The IMT-2020 vision for 5G enables a connected society that connects people, things, data, applications, transport systems and cities in a smart networked communications environment. This paper provides an overview of the key design principles and technology components for NR and the main features that distinguish NR from prior RATs developed by the 3GPP.

1. 5G Mobile Communications

As shown in Figure 1, mobile communications have evolved since the early 1980s when the 1st generation (1G) analog cellular communications systems were introduced. Commercial deployment of 1G made mobile telephony available for the first time on a large scale.

The 2nd generation (2G) cellular communications systems emerged in the early 1990s and made mobile telephony more available and wide-spread than previous 1G systems. The distinguishing feature of 2G is the transition from a purely analog system to a digital system. Additionally, 2G introduced new features such as supplementary services, short message services, and a limited form of wireless cellular data.

The 3rd generation (3G) cellular communications systems were introduced in the early 2000s. The 3GPP 3G is based on wideband code division multiple access (WCDMA)-based radio access technology which later evolved into high speed packet access (HSPA) technology. 3G expands the limited mobile data capability of 2G to mobile broadband, allowing high speed wireless internet to become available with the introduction of HSPA and HSPA+ in releases 6 and 7 of the 3GPP, respectively.

The 5G system increases the achievable data rate, improves system efficiency and the mobile broadband experience. However, the scope of the 5G extends beyond mere enhancement of mobile broadband.

3GPP standardization of the 4th generation (4G) cellular communications systems began in 2008 with release 8 and the introduction of long term evolution (LTE) and later LTE-Advanced and LTE-Advanced Pro. 3GPP 4G systems rely on a multiple input and multiple output-orthogonal frequency division multiplexing (MIMO-OFDM) physical layer as well as enhanced throughput and efficiency. This created an even better mobile broadband experience than previous 3G systems. In addition, 3GPP 4G systems achieve higher data rates, making demanding services such as video streaming possible.

The 5G system increases the achievable data rate, improves system efficiency and the mobile broadband experience. However, the scope of the 5G extends beyond mere enhancement of mobile broadband. The 5G enables wireless connectivity for any kind of device, leading to what is commonly described as the Internet of Things (IoT). The high data rate and the improved system

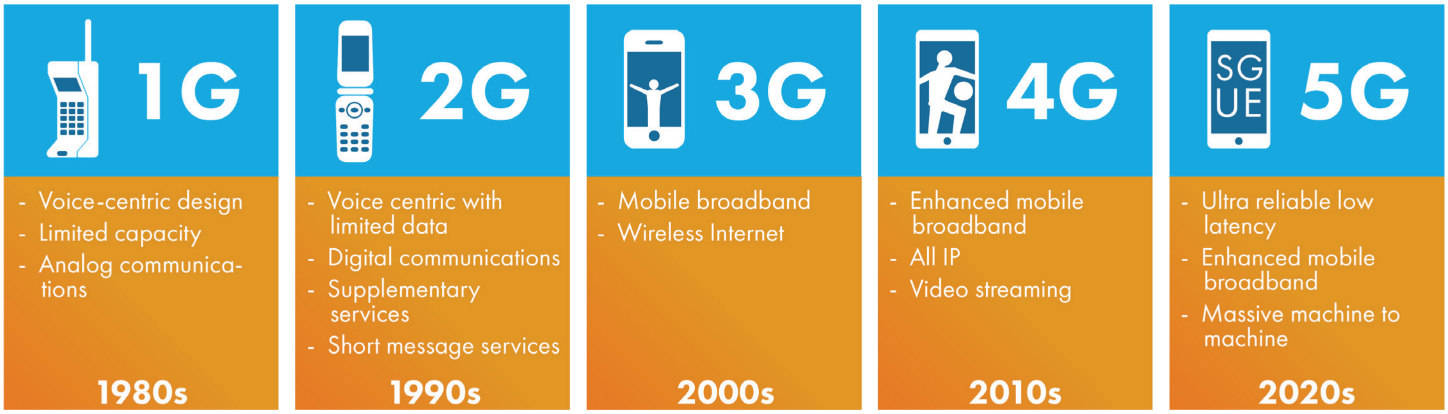

Figure 1: Evolution of Mobile Communications

architecture provided by the 5G, enables a wide range of innovative applications and future use cases which are not implemented by current cellular technologies.

1.1 Capabilities and Requirements

Similar to the current cellular communication systems, enhancing peak and average data rates to improve the user experience for mobile broadband continues to be the most important goal for 5G. Peak data rates as high as 10 Gbps or more are estimated for the 5G. In addition, 5G strives to improve the data rate in different types of situations including urban, suburban and rural environments.

Low latency plays an important role in the mobile broadband experience. For example, in applications envisioned in 5G, such as vehicle-to-network (V2N) communications for traffic safety, low latency plays a critical role. End-to-end latency in the order of 1 ms is required for 5G. In order to achieve the 1 ms end-to-end latency requirement, the radio-access network only contributes to a small portion of the overall 1 ms latency.

Requirements for the 5G system include high reliability, both in terms of low error-rate communication links (e.g., with bit error rate below 10^{-9}) and reliability in terms of maintaining connectivity, even in the case of unexpected events such as natural disasters.

Similar to IMT-2000 and IMT-Advanced, which set the stage for research activities around 3G and 4G, IMT-2020 is associated with 5G wireless access.

The 5G system also supports applications that require collection of data from low cost sensors and devices with limited capabilities. These applications typically require modest requirements in terms of data rates and latency. The energy consumption of these devices may be extremely low to allow for several years of battery life.

1.2 IMT-2020 Requirements and Usage Scenarios

The ITU activities that define the vision for the 5th generation cellular communications system, referred to as IMT-2020, started in 2013. Similar to IMT-2000 and IMT-Advanced, which set the stage for research activities around 3G and 4G, IMT-2020 is asso-

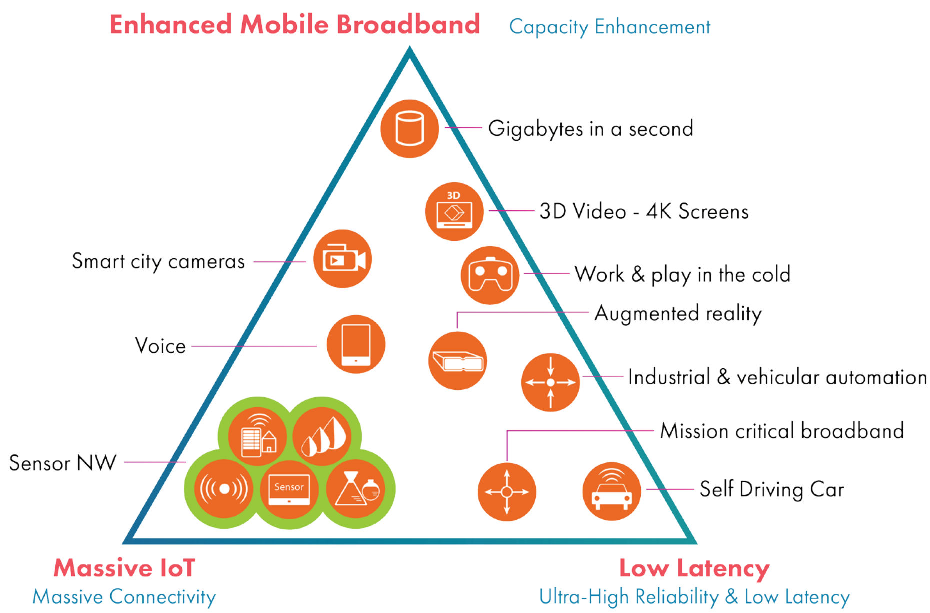

Figure 2: 5G Usage Scenarios

The 5G system utilizes significantly higher frequency bands when compared to previous generations of cellular communications systems.

ciated with 5G wireless access. As shown in Figure 2, ITU has defined the following basic usage scenarios for 5G:

Enhanced mobile broadband (eMBB): The eMBB usage scenario includes both small-area (e.g., hot spots) as well as wide-area coverage. The solutions for small-area coverage enable higher data rates, user density and capacity. Solutions for wide-area coverage focus on mobility and a seamless user experience, with lower requirements on data rate and user density. In general, the eMBB addresses human-centric communication.

Ultra-reliable and low-latency communications (URLLC): Both human-centric communications and machine-centric communications are covered by URLLC usage scenarios. These use cases generally have stringent latency, reliability and high availability requirements. Examples of usage scenarios include V2N communications involving safety, wireless control of industrial equipment, remote medical surgery, and distribution automation in smart grids.

Massive machine-type communications (M-MTC): This is a pure machine-centric communication use case, where small data transmissions with high resilience to delay are transmitted by a large number of connected devices. The M-MTC devices generally have a very long battery life.

1.3 Spectrum for 5G

The 5G system utilizes significantly higher frequency bands when compared to previous generations of cellular communications systems. While operation in low-frequency bands allows better coverage due to the low propagation loss, the continuously increasing demand for data has driven 5G to use additional higher-frequency spectrum bands. This pattern follows previous generations of cellular communications systems. While 1G merely operated in the sub-1 GHz frequency bands, 4G expanded the spectrum to up to 3.5 GHz. The first phase of 5G supports operation in spectrum up to approximately 30 GHz. Later phases of 5G expand the frequency bands by as much as 60–70 GHz or more.

By operating at higher frequency bands than the current cellular communications systems, the 5G system allows a given antenna area to be covered by a larger number of antenna elements that are not currently feasible with 1G through 4G systems. This enables highly effective antenna gain at the receiver side as well as highly effective receiver-side beamforming. When coupled with transmitter-side beamforming, the higher frequency bands provided by the 5G system allow extended ranges for point-to-point communication links. However, the deterioration of the non-line-of-sight conditions and penetration loss at higher frequencies makes communications at these high frequency bands challenging. Therefore, 5G services will employ the frequency bands of up to 10 GHz as the backbone for cellular communications. Frequency bands beyond 10 GHz will be utilized in dense outdoor and indoor deployments in order to provide high traffic capacity and high data rates.

However, the deterioration of the non-line-of-sight conditions and penetration loss at higher frequencies makes communications at these high frequency bands challenging.

2. General Design Principles

2.1 Evolution and Forward Compatibility

After its initial introduction, every successive generation of cellular communications system has evolved to be backward compatible, e.g., GSM to EDGE or WCDMA to HSPA or LTE to LTE-Advanced and LTE-Advanced Pro. For 5G RAT, the backward compatible evolution of technology supports the transition of specifications per a phased approach. Forward compatibility of NR will ensure smooth introduction of future services and features, while still allowing efficient access of earlier services and wireless devices. Exclusive signaling to NR wireless devices indicate reserved resources, ensuring forward compatibility of the NR.

While the evolution of NR will be backward compatible with its original introduction, the NR itself is not backward compatible with prior 3GPP technologies such as LTE.

Forward compatibility of NR will ensure smooth introduction of future services and features, while still allowing efficient access of earlier services and wireless devices.

2.2 Minimizing Always-On Transmissions

In legacy cellular communications systems, regardless of the data transmission and reception by wireless devices in a coverage area, certain signals are transmitted regularly by the base station. For example, in LTE, as shown in Figure 3, primary and secondary synchronization signals, cell-specific reference signals and system information are always transmitted by the base station. This "always-on" behavior can lead to increased interference and inefficient network operation. Although LTE has solutions to minimize the always-on transmissions (e.g., small-cell on/off mechanisms), these solutions depend on device capabilities and are not used widely by the LTE ecosystem. The introduction of the 5G NR, which is not constrained by backward compatibility to earlier technologies, enables more flexibility to design an ultra-lean radio access technology.

2.3 Packing the Transmissions in the Time-Frequency Grid

One design principle for NR is that transmissions are kept together and not spread out over a resource space. As shown in Figure 4, the transmissions and corresponding

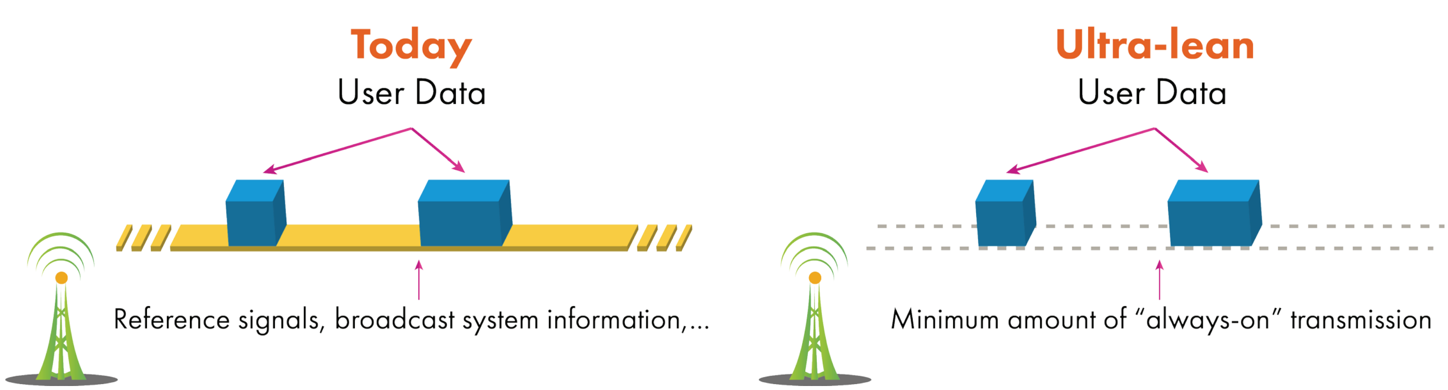

Figure 3: Minimizing Always-On Transmissions

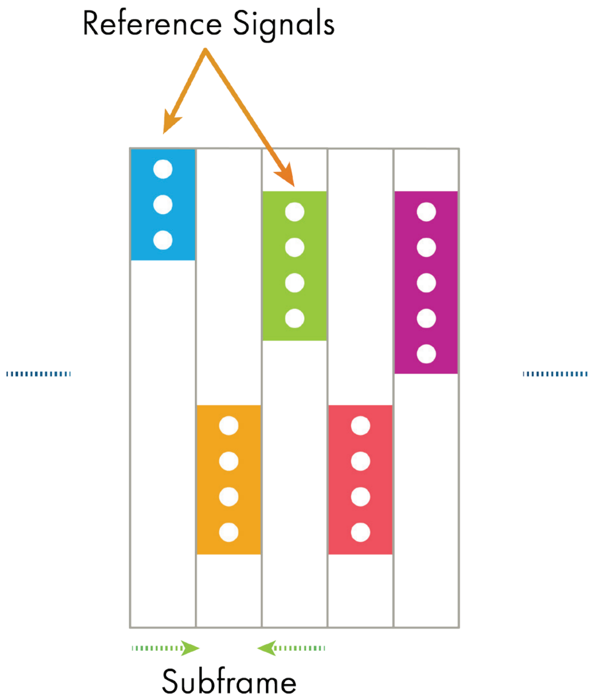

Figure 4: Packing Transmissions

reference signals are kept together in the OFDM time–frequency grid. This is helpful in achieving a high degree of forward compatibility. For example, the downlink control information in the NR is transmitted in control sub-bands which are smaller than the entire carrier bandwidth. Using this principle makes it easier to introduce new types of transmissions later in parallel to legacy transmissions, while still keeping backward compatibility.

This principle was not considered in the prior 3GPP RATs. For example, in LTE, the physical control format indicator channel (PCFICH), physical hybrid-ARQ indicator channel (PHICH), and physical downlink control channel (PDCCH) are transmitted in the control region of a subframe. PCFICH, PHICH, or PDCCH transmissions occupy the entire carrier bandwidth. This structure is helpful to achieve a high degree of frequency diversity and achieve randomization between transmissions. However, introducing new transmissions within the LTE control region is extremely difficult unless the new transmissions are fully aligned with the current control channel structure.

2.4 Flexible Timing Relationship

Another design principle for the 5G NR is to provide a flexible timing relationship across subframe borders and between different transmission directions. As an example, as shown in Figure 5, the LTE uplink hybrid-ARQ procedure employs a strict timing relationship where downlink acknowledgments and uplink retransmissions occur at predefined time instants that are relative to an initial transmission. This static timing relationship makes it more difficult to introduce new transmission procedures that are not completely aligned with the legacy timing relationship. In addition, this timing relationship was specified during the early development of the LTE standard and has not been updated to meet advances in processing capabilities that enable a shorter hybrid-ARQ round-trip time and consequently lower latency.

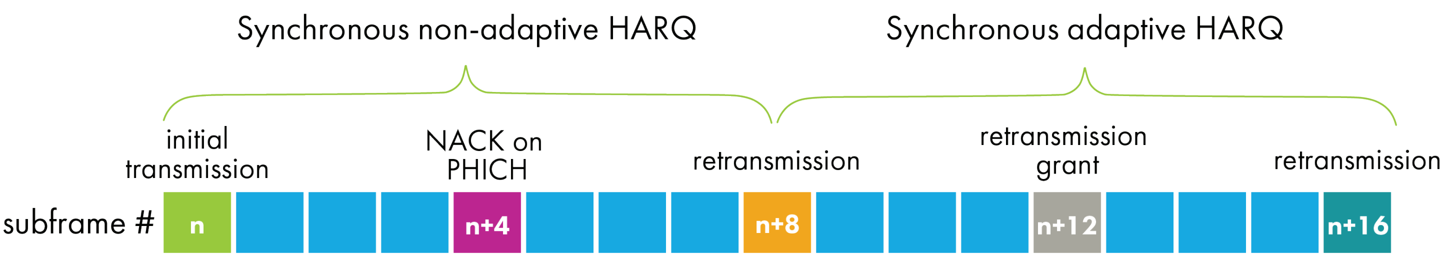

Figure 5: Uplink HARQ in LTE (Synchronous Adaptive or Non-Adaptive)

NR uses a scalable OFDM framework with different numerologies derived by scaling of a common baseline numerology.

3. Key Technology Components

3.1 Waveform

OFDM is the main candidate for both uplink and downlink transmissions in the 5G NR. Using the same waveform in both uplink and downlink simplifies the overall system design, particularly in respect to wireless backhaul and sidelink communications.

Due to the wide range of spectrum and deployment types, multiple OFDM numerologies are considered for NR. For the lower parts of the 5G spectrum (e.g., up to 5GHz), the same subcarrier spacing as LTE is sufficient. For higher frequencies, a larger subcarrier spacing is needed to ensure robustness against phase noise at a reasonable cost and power consumption for wireless devices. For example, in wide-area coverage deployment of 5G RAT in rural deployments, a cyclic prefix in the same order or larger than LTE is needed to handle large delay spread. However, for indoor deployments, a smaller cyclic prefix is sufficient. Wide-area deployments with larger cyclic prefix requirement typically operate at lower frequencies for which a lower subcarrier spacing is satisfactory. On the other hand, denser deployments with smaller cyclic prefix requirements typically operate at higher frequencies with larger subcarrier spacing requirements. NR uses a scalable OFDM framework with different numerologies derived by scaling of a common baseline numerology. As shown in Figure 6, different numerologies are multiplexed within the same NR carrier bandwidth.

3.2 Duplexing

Frequency division duplex (FDD) and time division duplex (TDD) have both been employed by LTE for two-way wireless communications in both paired spectrum and unpaired spectrum. The 5G RAT employs paired spectrum and unpaired spectrum and supports both TDD and FDD schemes. For the lower part of the 5G spectrum, paired spectrum with FDD dominates. In the higher part, which is limited to dense deployments due to propagation constraints, unpaired spectrum and TDD plays a more important role.

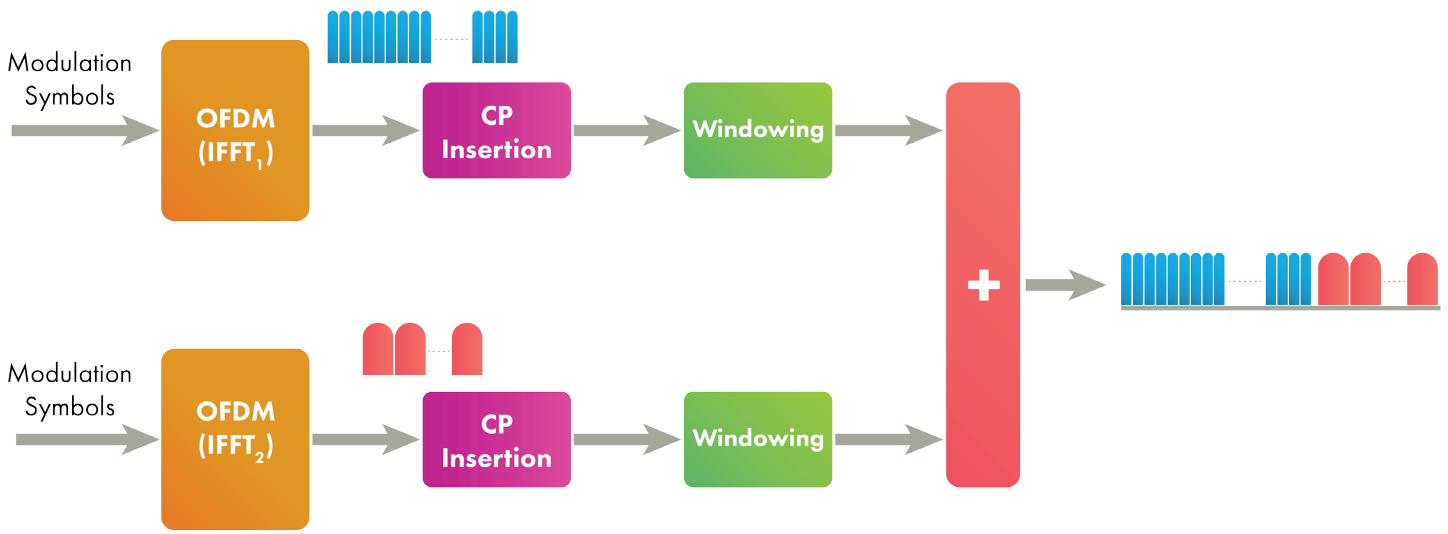

Figure 6: Mixing OFDM Numerologies

3.3 Frame Structure

The frame structure for the 5G NR supports operation in both paired and unpaired spectrums, as well as licensed and unlicensed spectrums. In addition, the frame structure is applicable to sidelink communication.

The frame structure helps achieve the low latency requirement by minimizing the latency over the radio link. One approach to decrease the latency is by utilizing a short transmission time interval (TTI). For example, to achieve the short end-to-end latency requirements of some URLLC applications, TTI as short as one OFDM symbol duration is needed. Control information such as scheduling assignments and reference signals employed for channel estimation are located at the beginning of the subframe in order to enable fast demodulation and decoding of data without waiting for the entire subframe to be received. Similarly, for uplink data transmissions, the scheduling grant can be transmitted at the beginning of the subframe with the corresponding uplink data filling the remainder of the uplink subframe. Scheduling decisions can control the uplink or downlink direction of the data transmission at any given time, resulting in a dynamic TDD scheme.

Subframe aggregation is considered in the NR. Subframe aggregation refers to the effective creation of a long subframe where multiple short subframes are dynamically aggregated for a single transmission with control information transmitted in the first subframe.

3.4 Beamforming

The single user – multiple input and multiple output (SU-MIMO) as well as the multi user – multiple input and multiple output (MU-MIMO) that were introduced in LTE, are also used in the NR. However, at high frequencies, coverage is a limiting factor. To counteract this issue, 5G employs beamforming as a fundamental and critical feature to enhance coverage at higher frequencies. There are challenges in the use of beamforming in the NR that need to be addressed. For example, broadcast channels that are used to deliver system information may not work if beamforming is used extensively. Beam finding and beam tracking solutions are also supported for the NR.

3.5 Multi-Site Connectivity

Multi-site connectivity plays an important role in 5G, particularly when operating at high carrier frequencies or when very high reliability is required. At high frequencies, wireless connectivity can be intermittent or may be temporarily lacking due to high diffraction loss. Multi-site connectivity provides diversity and improves reliability since the likelihood of poor links to antenna sites decreases when there is an increase in the number of antenna sites.

In addition, multi-connectivity can raise user data rates by increasing the effective channel rank for a wireless device and transmitting a larger number of layers when compared to a single-site scenario. The transmission resources at the neighboring site, which may be unused due to a lack of traffic, can be used to increase a user's data rate.

At high frequencies, coverage is a limiting factor. To counteract this issue, 5G employs beamforming as a fundamental and critical feature to enhance coverage at higher frequencies.

The 3GPP standardization roadmap for 5G RAT is driven by market demand for the early deployment of 5G networks and the need for the 5G specification to satisfy ITU IMT-2020 requirements.

3.6 Scheduled and Unscheduled Transmissions

Normal NR operation follows LTE schedule-based uplink transmissions. However, the process of transmitting the scheduling request, waiting for the scheduling decision by the base station, and then processing the uplink transmission grant is time-consuming. It can be difficult to achieve the latency requirement in many latency-critical applications that will be based on the NR. NR will, in addition to the schedule-based transmission, provide mechanisms for unscheduled uplink transmissions. To avoid inefficiency caused by possible collision and retransmission, mechanisms such as low-density spreading (LDS) and sparse-code multiple access (SCMA) are efficient ways to handle collisions.

3.7 Access/Backhaul Convergence

The requirements and characteristics of the wireless backhaul and access links converge in the 5G system. Due to the expansion of operations to higher frequency bands, the same frequency bands that are employed for the access links are also employed for the wireless backhaul. In addition, due to the existence of large numbers of indoor and outdoor base stations, the wireless backhaul operates in line-of-sight and non-line-of-sight propagation conditions, similar to access links. From the wireless transmission perspective, there are no major differences between the wireless backhaul link and the normal wireless link in the 5G system. Therefore, the convergence of backhaul and access in terms of spectrum and transmission procedures happen in the 5G RAT.

4. 3GPP Standardization Timeline

The 3GPP standardization roadmap for 5G RAT is driven by market demand for the early deployment of 5G networks and the need for the 5G specification to satisfy ITU IMT-2020 requirements. To achieve both these objectives, the 5G RAT standardization will occur in two phases. As described in Figure 7 below, the first phase of the specification will be based on 3GPP release 15, and is expected to be completed by September 2018. This will pave the way for a first wave of deployment in 2020. The second phase of the specification includes features needed to fulfill IMT-2020 requirements. This will be based on the 3GPP release 16, which is expected to be completed by the end of 2019. The commercial deployment of release 16-based 5G networks can begin as early as 2021.

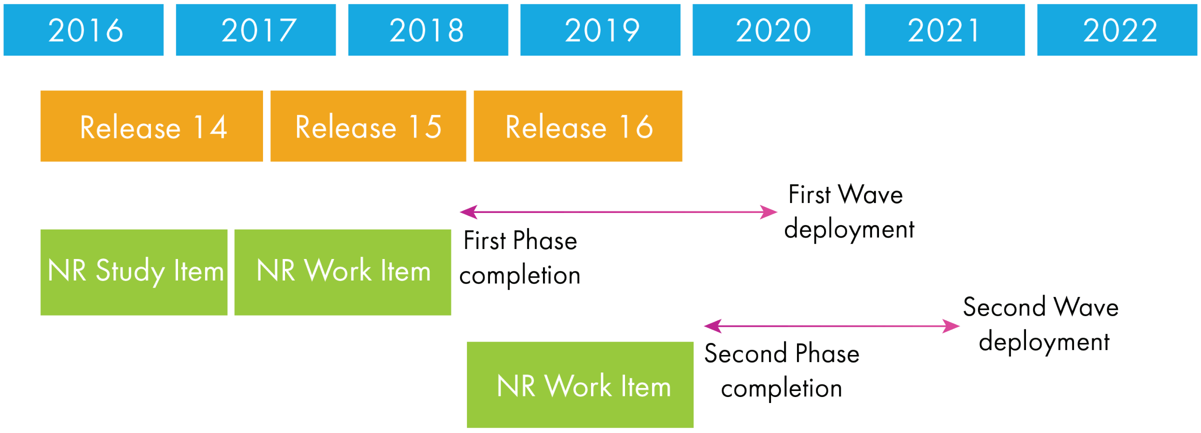

Figure 7. 3GPP NR Standardization Roadmap

Glossary

3GPP .... 3rd Generation Partnership Program
ARQ .... Automatic Repeat Request
EDGE .... Enhanced Data Rate for GSM Evolution
EMBB .... Enhanced Mobile Broadband
FDD .... Frequency Division Duplexing
GSM .... Global System for Mobile Communications
HARQ .... Hybrid Automatic Repeat Request
HSPA .... High Speed Packet Access
IMT .... International Mobile Telecommunication
IoT .... Internet of Things
ITU .... International Telecommunication Union
LDS .... Low Density Spreading
LTE .... Long Term Evolution
M-MTC .... Massive Machine Type Communication
MIMO .... Multiple Input Multiple Output
MU-MIMO .... Multi-User MIMO
NR .... New Radio
OFDM .... Orthogonal Frequency Division Multiplexing
PCFICH .... Physical Control Format Indicator Channel
PDCCH .... Physical Downlink Control Channel
PHICH .... Physical HARQ Indicator Channel
RAT .... Radio Access Technology
SCMA .... Sparse Code Multiple Access
SU-MIMO .... Single-User MIMO
TDD .... Time Division Duplexing
TTI .... Transmission Time Interval
URLLC .... Ultra-Reliable Low Latency Communication
V2N .... Vehicle to Network
WCDMA .... Wideband Code Division Multiple Access

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About the Author

Alireza Babaei is currently a senior researcher at Ofinno Technologies focusing on research and development of radio access network procedures for LTE Advanced, LTE Advanced Pro and New Radio for 5G. Prior to his current position, he held senior research positions at CableLabs and Wireless@VT and actively participated in 3GPP, IEEE 802 and Wi-Fi Alliance. Alireza is the recipient of an outstanding graduate student award in 2009, 2012 Journal of Communications and Networks best paper award, and IEEE ICC 2012 wireless networking symposium best paper award. He was a guest editor for Aug. 2010 issue of IEEE Wireless Communication Magazine, an organizer of IEEE ICC 2015 workshop on "LTE over unlicensed bands," and the industry presentations chair of IEEE GLOBECOM 2016. He has authored more than 35 publications in international conferences and journals and is an inventor in more than 40 granted or pending US patents. He received his Ph.D. degree in Electrical and Computer Engineering from George Mason University, Fairfax, Virginia, USA in 2009. He is a senior member of IEEE.

About Ofinno

Ofinno develops wireless technologies that address some of the most important technological issues in today's modern life. Our wireless technology innovators create new technologies that have an astounding 67% utilization rate, producing tangible results for both wireless device users and carriers alike. At Ofinno, the people inventing the technologies are also the people in charge of the entire process, from the idea, through design, right up until the technology is sold. Ofinno's research focuses on fundamental issues such as improving LTE-Advanced performance, Mission Critical Services, Inter-Band Carrier Aggregation, New Radio for 5G, V2X, IoT, and Power Management. Our team of scientists and engineers seek to empower mobile device users, and the carriers that serve them, through cutting edge network performance innovations.