New Radio (NR) and Its Evolution toward 5G-Advanced

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Abstract

New Radio (NR), which is part of Release 15 of Third Generation Partnership Project (3GPP) standards, marks the first fifth generation (5G) standards designed to meet the requirements set forth by the International Telecommunication Union for IMT-2020. This article presents an overview of the NR radio interface and the ongoing work in 3GPP to evolve NR toward 5G-Advanced, allowing it to access new spectrum and support a broader range of vertical services while enhancing its performance beyond what is available today.

Introduction

Cellular mobile communications have been constantly evolving over the last couple of decades to become an essential part of everyone's day-to-day life. Starting with simple applications such as voice calls and messaging using analog wireless technology, it has now evolved to an IP-based digital technology that supports applications that reach out to every corner of our lives in the form of videos, Internet access, the Internet of Things (IoT), and public safety. At the heart of this evolution is the Third Generation Partnership Project (3GPP), which has been developing the standards necessary for cellular mobile communications for over 20 years.

Since 1998, 3GPP has developed the de facto standards for cellular mobile communications; 3G wideband code-division multiple access (WCDMA)/high-speed packet access (HSPA), 4G LTE/LTE-Advanced, and recently 5G New Radio (NR). With the development of 5G NR standards in 3GPP Release 15, the performance and functionality of cellular mobile communications have reached an unprecedented level. Compared to LTE/LTE-Advanced, NR can support faster data rates, lower latency, higher reliability, and new spectrum bands. The key requirements of 5G as defined by the International Telecommunication Union — Radiocommunication Standardization Sector (ITU-R) are summarized in Fig. 1 [1].

Although the first release of NR standards has been completed, 3GPP's work on evolving the NR standards to fulfill the vision of 5G is still ongoing and expected to continue for a number of years. This ongoing evolution is necessary since the vision of 5G is not only about surpassing LTE in performance metrics but also about supporting new verticals and new spectrum in a way that is not possible in LTE.

The rest of this column is organized as follows. A summary of the performance of NR along with its functional features is provided. An introduction to the key features expected to be standardized in future releases of NR is provided. Specifically, technical areas related to extending NR's deployable spectrum, supporting new applications, and enhancing the mobile broadband performance are discussed. The final section provides concluding remarks.

Release 15 New Radio: The Start of 5G

Performance of NR Compared to LTE-Advanced

NR adopts orthogonal frequency-division multiplexing (OFDM)-based waveform for both downlink and uplink with a subcarrier spacing (SCS) of $2^n \times 15$ kHz where $0 \le n \le 3$ for data transmission. The applicable SCS depends on the frequency band and deployment scenario. Table 1 summarizes the newly defined NR bands, applicable SCSs, and the maximum bandwidths with and without carrier aggregation (CA).

Note that NR can be deployed not only on these newly introduced bands but also on bands previously defined for LTE in FR1. Compared to NR, LTE-Advanced can only support a single SCS of 15 kHz and CA with up to 5 component carriers (CCs) resulting in a maximum aggregated bandwidth of 100

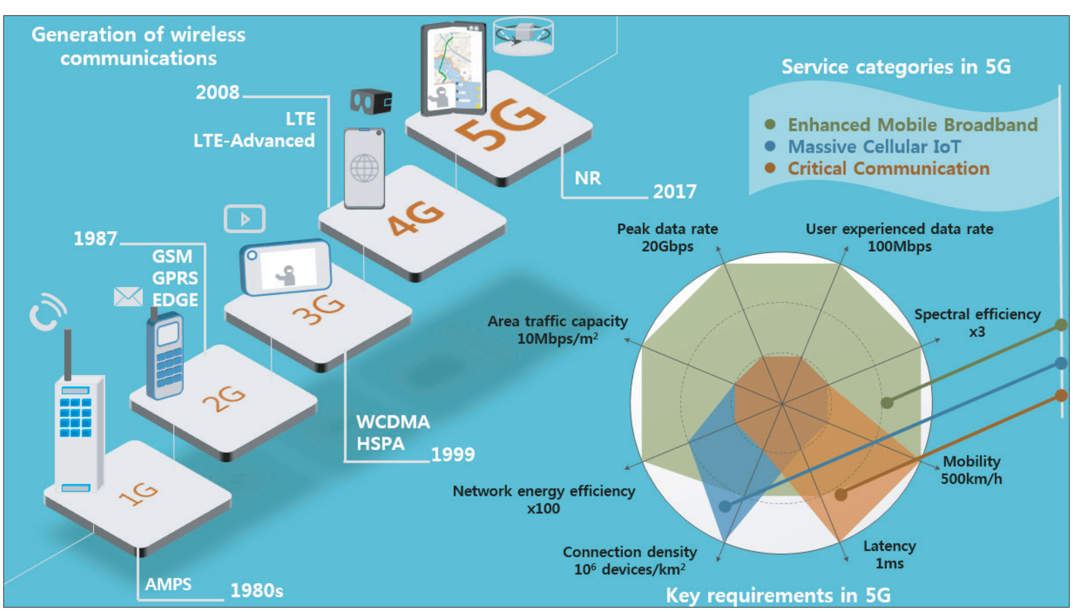

FIGURE 1. Key requirements of 5G cellular mobile communications as defined by ITU-R.

	Applicable frequency range	Newly defined NR bands	Applicable SCSs for data transmission	Maximum bandwidth
Frequency range 1 (FR1)	450 MHz~7.125 GHz	n77 (3.3~4.2 GHz) n78 (3.3~3.8 GHz) n79 (4.4~5 GHz)	15/30/60 kHz	100 MHz per CC, 1.6 GHz for CA (16CCs)
Frequency range 2 (FR2)	24.25~52.6 GHz	n257 (26.5~29.5 GHz) n258 (24.25~27.5 GHz) n260 (37~40 GHz) n261 (27.5~28.35 GHz)	60/120 kHz	400 MHz per CC, 6.4 GHz for CA (16CCs)

TABLE 1. Newly defined NR bands and applicable subcarrier spacings.

	LTE-Advanced (Release 10)	NR (Release 15)
Peak data rate for downlink	Without CA: 600 Mb/s With CA (5 CCs): 3 Gb/s	Without CA: 4.9 Gb/s for FR1, 10.7 Gb/s for FR2 With CA (16 CCs): 78.2 Gb/s for FR1, 171.2 Gb/s for FR2
Peak data rate for uplink	Without CA: 300 Mb/s With CA (5 CCs): 1.5 Gb/s	Without CA: 2.4 Gb/s for FR1, 4.0 Gb/s for FR2 With CA (16 CCs): 38.2 Gb/s for FR1, 64.6 Gb/s for FR2
Average spectral efficiency	Downlink: 3.2 bps/Hz Uplink: 2.5 bps/Hz	Downlink: 13.9 b/s/Hz Uplink: 7.7 b/s/Hz
Achievable minimum air latency	4.8 ms	0.48 ms
Maximum mobility	350 km/h	500 km/h

TABLE 2. Key performance comparison between Release 15 NR and Release 10 LTE-Advanced.

MHz. Also, LTE-Advanced does not support deployment on FR2. Table 2 compares NR with LTE-Advanced in terms of performance as summarized in [2].

In terms of peak data rate, NR can support a much higher rate than that of LTE-Advanced, mainly due to its larger bandwidth per CC and its ability to aggregate up to 16 CCs compared to 5 CCs for LTE-Advanced. For example, the downlink peak data rate of LTE-Advanced is 3 Gb/s, whereas it is 171.2 Gb/s for NR in FR2.

In terms of average spectral efficiency, which is the aggregate throughput of all users divided by the channel bandwidth of a specific band, NR prevails again over LTE-Advanced. The improvement in spectral efficiency is achieved mainly from the more advanced antenna technology, which is able to utilize more antennas at a gNB (3GPP terminology for base station) and UE (3GPP terminology for terminal). LTE-Advanced achieves 3.2 b/s/Hz for downlink and 2.5 b/s/Hz for uplink, while NR is able to achieve 13.9 b/s/Hz for downlink and 7.7 b/s/Hz for uplink. While the improvement in peak data rate requires additional frequency resources, the improvement in average spectral efficiency can be achieved even if the available frequency resources for NR and LTE are the same. The improvement in average spectral efficiency makes NR an attractive candidate for FR1 even if the available frequency resources are limited.

Besides the superior peak data rate and average spectral efficiency, NR is better than LTE-Advanced in terms of air latency, which is the time from the moment a source sends a packet until the targeted destination receives it without error. With an air latency that is 1/10th of LTE, NR is suitable for next generation applications such as industrial automation and augmented reality. Furthermore, NR can maintain a sufficient quality of service even at a maximum UE speed of 500 km/h, transfer data with a reliability of 99.9999 percent or higher, and support simultaneous connections of over 10^6 devices within an area of 1 km^2.

Key Functional Features

NR has adopted a number of key functional features to accommodate different network deployment scenarios, terminal requirements, and applications over the air interface.

One such feature is bandwidth part (BWP), which is basically a portion of a carrier bandwidth that is configured to a UE. In LTE/LTE-Advanced, where the maximum carrier bandwidth is 20 MHz, a UE has to monitor the entire bandwidth. However, for NR, the same approach could result in excessive power consumption at the UE since NR has a much larger bandwidth. While having a larger bandwidth is essential for supporting a higher data rate, depending on the application, it might not be absolutely necessary. For example, a voice call, which requires an average data rate smaller than 100 kb/s, can be handled with less than 5 MHz. Using the entire carrier bandwidth to support such a low-rate service would cause severe power consumption at the UE due to the high sampling rate necessary for the larger bandwidth. BWP can be used in such situations so that the UE monitors a smaller portion of the carrier bandwidth that is tailored for the UE's application.

In NR, a UE can be configured with up to four BWPs for a carrier, each with configurable location and size. At a given time, the UE can receive data transmission on only one of the four BWPs. The possibility of switching between multiple BWPs makes it possible for the UE to change its RF bandwidth according to the data rate that needs to be supported. Furthermore, for those time instances where there is no data to transmit, a BWP with the smallest size may be chosen so as to minimize a UE's power consumption.

Another key feature of NR that is not supported in LTE-Advanced is codeblock group (CBG)-based retransmission. In NR, a transport block (TB), which is the basic unit for data transmission, can be divided into up to eight CBGs. For each CBG, an individual hybrid automatic repeat request acknowledgment (HARQ-ACK) feedback is indicated by the receiving side so as to notify the transmitting side which of the CBGs were received correctly and which were not. This feature is especially useful

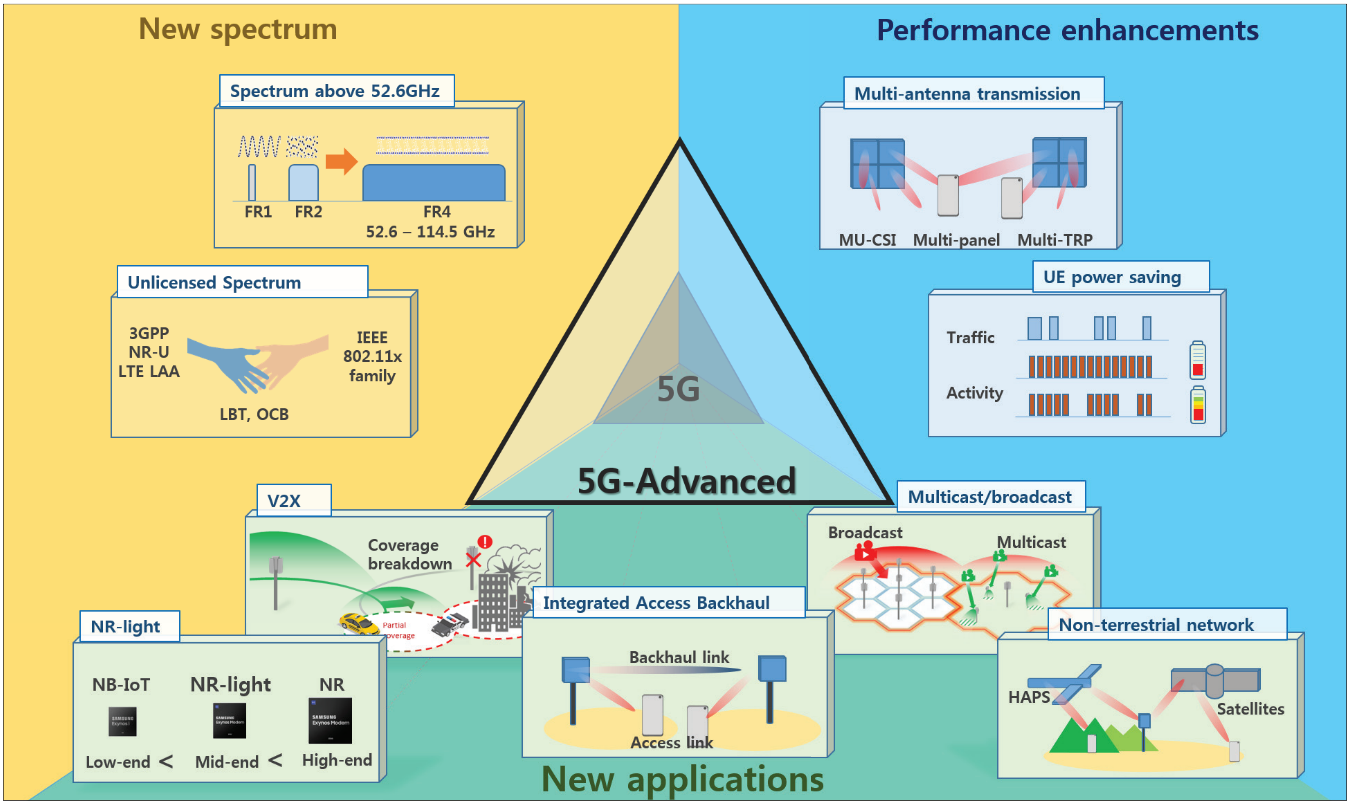

FIGURE 2. Evolution toward 5G-advanced.

when delay-tolerant data transmissions are partially corrupted by transmissions for urgent data packets. As shown in [3], CBG-based retransmission provides significant performance gain since less time-frequency resources are used for retransmissions, making more room for other data.

Perhaps the most important functional feature of NR worth mentioning is the support for multi-beam operation. Although multi-antenna technology has been heavily used in LTE-Advanced as well, it was mainly for the purpose of maximizing spectral efficiency with better precoder design and larger number of antennas. In NR, multi-antennas are used not only for this purpose but also to ensure sufficient coverage for FR2 where propagation loss is much more severe than FR1. For example, the signal attenuation of 28 GHz is 100 times larger than that of 2 GHz.

NR utilizes multi-beam operation to overcome such large propagation loss in FR2 by realizing multiple highly directional beams using a large number of antenna elements. In a given time instance, only one of multiple beams which provides sufficient signal quality is used for data transmission. NR provides the necessary specification support for measurement, selection, and assignment in order to operate such multi-beam operation.

Release 16/17 New Radio: Evolution toward 5G-Advanced

Release 15 NR provides the foundation on which 3GPP will continue its work to evolve the capability and functionality of 5G so as to support new spectrum and new applications, and further enhance existing core features. Over a period of three years, starting from mid-2018 until mid-2021, 3GPP will undertake the next phase of 5G: the evolution toward 5G-Advanced. Figure 2 summarizes the key features to be introduced in Releases 16 and 17 from the physical layer perspective over the course of three years.

Evolution toward New Spectrum

Support for Unlicensed Spectrum: Unlicensed spectrum has not been widely exploited by cellular communications until recently. LTE-Advanced introduced specification support to access unlicensed spectrum with assistance from a licensed carrier using the CA framework (LAA or licensed assisted access). In Release 16 NR, specification support for NR-Unlicensed (NR-U) will be introduced so that unlicensed spectrum can be accessed with NR as well. One key difference of NR-U compared to LAA is that unlicensed spectrum can be accessed without any assistance from a licensed carrier. Since a licensed carrier is not a necessity, NR-U can be deployed by any party, creating new opportunities for applications in the form of private networks for industrial automation, retail stores, hospitals, schools, and so on. In addition, NR-U also supports a licensed assisted mode of operation that is similar to LAA with better channel access performance and wider bandwidth operation.

The main challenge of NR-U is addressing the regulatory requirement that a transmitter has to "listen to" the channel before "talking" for fair coexistence with any devices operating in the same unlicensed spectrum. Unlike NR in licensed spectrum, critical signal/channel for communication such as those for synchronization, control, and random access may not be transmitted on unlicensed spectrum unless the channel is determined to be idle beforehand. Consequently, NR-U will focus on the specification support to provide additional transmission/reception opportunities for such signals/channels.

Furthermore, it is expected that additional enhancements on NR-U will be made in Release 17 to access unlicensed spectrum in higher bands (e.g., 60 GHz). For such high bands, a channel sensing mechanism coupled with multi-beam operation would be necessary to address hidden/exposed node problems.

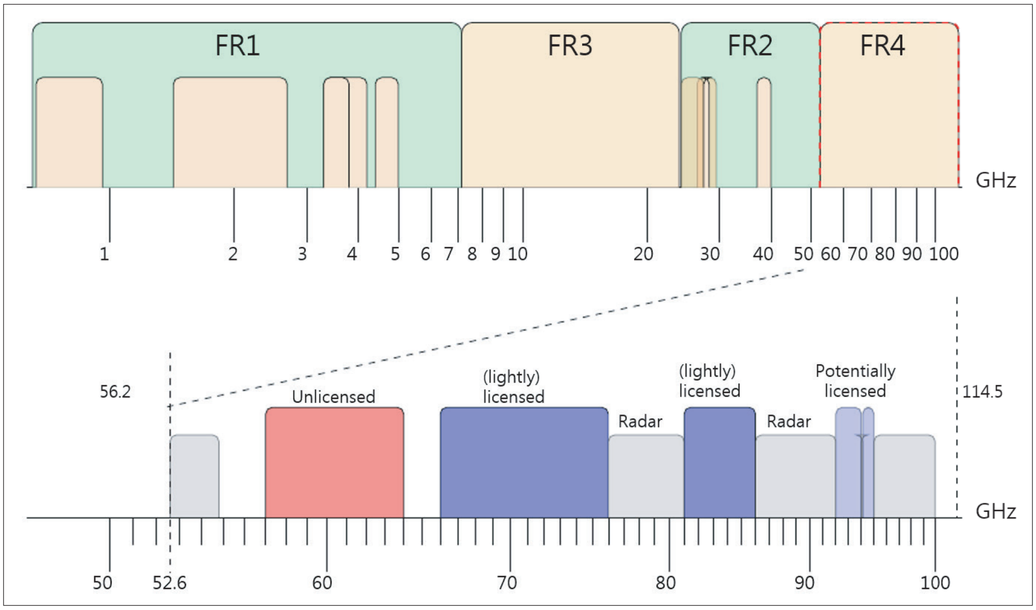

FIGURE 3. Spectrum above 52.6 GHz.

Support for Spectrum above 52.6 GHz: The initial target for NR was to design an air interface that can support carrier frequency up to 100 GHz. With Release 15 NR, the first part of this work has been completed for carrier frequency up to 52.6 GHz. The second part of the work for above 52.6 GHz that will open up V to W band (60~114.25 GHz) to NR will be done in Releases 17 and 18. This expansion is noteworthy because it provides not only ultra-wide spectrum up to 15 GHz, but also new opportunities for back/fronthaul, relay, industrial IoT, private network, advanced vehicle-to-everything (V2X), tightly coupled licensed-unlicensed spectrum usage, and minimizing form factors for future wireless devices.

However, there are several hurdles that need to be overcome in order to realize mobile communications for this band: high attenuation due to atmospheric gases, inefficient RF devices such as power amplifier, switch, and mixer due to in-device interference and attenuation, and severe shadowing by reflection and diffraction due to a short wavelength. In order to handle these issues, the air interface would need to be enhanced from a whole new perspective.

The first area in designing an air interface for spectrum above 52.6 GHz is the waveform. The existing NR waveform based on cyclic prefix OFDM works well in multipath channels but has coverage limitations due to high peak-to-average-power ratio (PAPR). Combined with the already low efficiency of RF components for this band, a high PAPR would have a severe impact on device battery life as well as coverage. In order to address the issues, a new waveform would have to be introduced along with all the physical layer channels redesigned accordingly.

The second area is the enhancement of beam operation. Operating in a much higher frequency would require higher beam gains to maintain sufficient coverage. However, higher beam gains would require more beams with narrower beamwidth compared to that of Release 15 NR. The beam operation would have to be optimized to handle a much larger number of beams but with minimized overhead and inefficiency.

The third area is the enhancements on multiple transmission reception point (multi-TRP) and multi-panel operation to maintain a line of sight (LoS) link between the transmitter and the receiver. In order to overcome the adverse propagation properties of this band, maintaining an LoS link would be critical. Since LoS might not be possible at a given time between a single TRP and a UE, the LoS link would have to be maintained using multi-TRPs or multi-panels based on position/angle tracking and point-beamforming.

Evolution toward New Applications

Multicast/Broadcast: For Releases 15/16, NR has focused on unicast data transmission between a gNB and a single UE. Compared to unicast, multicast and broadcast enable transfer of information in a one-to-many manner. In LTE-Advanced, evolved multimedia broadcast multicast service (eMBMS) was specified to enable broadcast transmission to multiple users. For eMBMS, multiple base stations transmit the same signal as in a single-frequency network to increase coverage. One drawback of this feature is that unicast and broadcast transmissions cannot be multiplexed flexibly in the frequency domain. Single cell point-to-multipoint (SC-PTM) is another feature developed for LTE-Advanced to complement eMBMS by enabling the possibility of frequency domain multiplexing between unicast and multicast transmissions.

Multicast and broadcast for NR have been identified as one of the key features to support use cases such as advanced driving, public safety, and efficient multimedia distribution. In order to minimize the overlap with eMBMS in LTE, NR multicast and broadcast will not target the scenarios with high-tower high-power deployment scenarios for broadcast over a very wide coverage area. On the other hand, NR multicast and broadcast will be designed to address more localized coverage and enable flexible resource multiplexing among unicast, multicast, and broadcast in time and frequency domains.

Compared to SC-PTM in LTE, NR broadcast and multicast are expected to achieve better performance in terms of throughput, reliability, and latency. In order to do so, link adaptation, multiple-input multiple-output (MIMO), HARQ, and feedback mechanisms are candidate features under consideration. Link adaptation will provide more efficient use of the wireless resources, while MIMO and HARQ mechanisms can be utilized to improve reliability and throughput.

NRL-light: Massive cellular IoT is one of the three usage scenarios defined by ITU-R [1]. For LTE, two technologies have been specified for this purpose: machine-type communications (LTE-M) and narrowband IoT (NB-IoT). Both technologies focus on the lower end of the IoT market for low-power wide area networks. LTE-M and NB-IoT support peak data rates of ~1 Mb/s and <160 kb/s, respectively, with at least 15 dB coverage extension and up to 10 years of battery life under certain conditions.

Despite the high performance of Release 15 NR, it might be overcomplicated for applications where high throughput, latency, and reliability are not critical. To address the situation, NR specification is expected to be extended to support a lighter version of NR, NR-light, for mid-market IoT devices such as smart watches, video surveillance cameras, and industrial sensors. The peak date rate of NR-light is expected to be 5~10 Mb/s, which is at least 100 times lower than the first NR devices based on Release 15 with better power saving and coverage. To avoid additional overhead due to the introduction of NR-light, Release 15 synchronization signal and PBCH can be reused for initial access. Assuming a 15 kHz subcarrier spacing, an NR-light UE would be required to support a 5 MHz RF bandwidth, which is 20 times smaller compared to that of Release 15. Narrower RF bandwidth and lower peak data rate would decrease UE complexity and power consumption. In addition, simplified air interface procedures, such as early data transmission, can be used to minimize latency and UE power consumption taking into account the characteristics of IoT traffic. Other schemes such as those under discussion for enhanced UE power saving (e.g., wake up signal) are also candidate features that can be used for NR-light.

Integrated Access and Backhaul (IAB): Compared to deployments on FR1, deployments on FR2 require much higher cell densification in order to provide sufficient coverage despite severe propagation loss. A key issue in such a high cell density scenario is how to connect the cells. Conventional cellular networks relied primarily on wired backhaul, but this approach would not be a good solution considering the cost of a wired backhaul deployment and the number of cells involved. To address this issue, 3GPP is in the process of developing IAB, which is a standardized wireless backhaul link intended to operate in the same spectrum as the access link.

IAB has several key features tailored for efficient operation in FR2. The first feature is its flexibility for multiplexing transmissions for access and backhaul links in frequency and spatial domains. Such multiplexing was not specified for LTE-Advanced relay since LTE has a much smaller bandwidth of 20 MHz per carrier. The second feature is that multihop transmission is supported to extend the coverage to UEs that are quite far from a gNB. Multi hop transmission was not specified for LTE-Advanced relay since it was not critical considering the propagation properties of FR1. The third feature is the ability to adaptively re-route traffic between IAB nodes if there is short-term blockage. The conventional approach would be to re-establish the backhaul link with another IAB node based primarily on higher-layer procedures and signaling. In order to maintain seamless service, a more aggressive approach that relies more on the physical layer is being considered to minimize latency and overhead.

Vehicle-to-Everything: For NR V2X, 25 use cases have been identified [4], which can be categorized into four groups:
- Vehicle platooning, which enables vehicles to dynamically form a platoon travelling together
- Extended sensors, which enable the exchange of raw or processed data gathered through local sensors or live video images among vehicles, roadside units, devices of pedestrians, and V2X application servers
- Advanced driving, which enables semi-automated or fully automated driving
- Remote driving, which enables a remote driver or an application to operate a vehicle for those passengers who cannot drive by themselves or vehicles located in dangerous environments

The above NR V2X use cases have more stringent requirements than those of LTE V2X, and as a result, the capabilities for NR to service vehicles over the access and sidelink would have to be significantly superior to that of LTE. The key target is to achieve lower latency and higher reliability while providing better system capacity and coverage. In order to do so, approaches including support of unicast sidelink operation and sidelink with link adaption are being considered. Furthermore, NR V2X-based sidelink operation can be used not only for vehicular applications but also for other applications such as public safety, which is one of the key functions for mission-critical communication. While many aspects of NR sidelink designed for V2X can be directly reused for public safety, there are a couple of aspects that are unique to public safety. Such aspects include UE-to-network relay for extending network coverage in case of natural disasters or terrorist attacks when parts of the network could be offline. In future NR releases, it is expected that these extensions will be added on top of the NR V2X framework to support public safety.

Non-Terrestrial Network (NTN): NTN is under study in 3GPP to provide services to users via space/airborne vehicles such as satellites and high altitude platform systems (HAPSs). With NTN, it is expected that the coverage of NR can be extended to underserved areas where the cost of deploying terrestrial networks is uneconomical for operators. In addition to the cost factor, the speed of deployment with spaceborne or airborne platforms could be much faster, enabling communities in under-served areas to reap the benefits of NR services far earlier. It also reinforces the NR service reliability under disaster and emergency circumstances where the terrestrial infrastructures could be inoperable.

The main technical challenge faced by NTN is due to its deployment scenarios being essentially different from terrestrial networks. Multiple deployment scenarios have been considered including GEO/non-GEO satellites and HAPSs. For a HAPS, the altitude is up to 50 km and the cell size is up to 200 km, which is still within the coverage design target of Release 15 NR. However, for satellites, especially for GEO satellites, the altitude is 35,786 km and the cell size is up to 1000 km. The extremely long distance between the satellite and UE leads to round-trip times on the order of hundreds of milliseconds. Such long delay and extended coverage impose significant challenges on random access, uplink timing, and any physical layer control procedure requiring feedback, such as link adaptation, MIMO, and HARQ. Another challenge for NTN is the extreme Doppler effects due to fast relative movement between the satellites, such as medium Earth orbit (MEO) and low Earth orbit (LEO) satellites and UE. For example, the maximum Doppler shift is ±48 kHz at 2 GHz carrier frequency for a LEO satellite at an altitude of 600 km.

eMBB Performance Enhancement

Enhanced MIMO: MIMO has been a key feature in NR to make cellular communications on FR2 a reality and achieve significantly improved spectral efficiency for FR1. Despite new breakthrough technologies in Release 15 NR-MIMO, there still remains much room for improvement, especially to address the following:
- Large overhead associated with channel status information for multi-user MIMO
- Limited number of beams

Considering the above, NR-MIMO for Release 16/17 will focus on three key areas. The first area is the compression of channel state information (CSI) across the spatial and frequency domain to find the optimum balance between CSI overhead and accuracy. The second area is the extension of beam management operation to handle more than 64 beams while keeping the associated signaling overhead manageable. This enhancement of beam management is especially critical since future NR will evolve toward deployment on carrier frequencies much higher than FR2. The third area is non-coherent joint transmission (NC-JT), which allows a UE to maintain multiple links with multiple TRPs simultaneously on the same carrier. One motivation for NC-JT is to enhance the reliability of NR for vertical applications such as industrial automation where redundant links can be utilized just in case one of the links fails.

Enhanced UE Power Saving: Release 15 NR has been designed to perform better than LTE in every aspect such as data rate, range of deployable spectrum, latency, and reliability. The inevitable consequence with such a design is an increased burden on the UE's battery. While providing unprecedented performance is important, if the associated power consumption is too high, it would have a negative impact on user experience. Naturally, UE power saving has been a key topic for Release 15 and continues to be of importance in Release 16.

UE power saving in NR exploits the intermittent pattern of real-life traffic. Relative to the active connection time, the actual time where data is scheduled is quite small. Due to such a traffic characteristic, UE consumes more power on control channel decoding compared to that of data channel decoding. To address UE power saving in such situations, several features were specified in Release 15 [5] such as BWP adaptation and configurability to adapt a UE's control channel monitoring. For example, when there is no traffic, a UE can be configured to operate in a very narrow BWP with a relaxed control channel monitoring periodicity and smaller number of blind decodes to minimize power consumption in its RF and baseband units.

Release 16 NR will further enhance UE power saving features to handle more dynamic changes of the traffic using fast control channel monitoring adaptation along with optimization of UE procedures for data channel reception in the time/frequency/antenna domain.

Conclusions

Over 1000 standardization engineers from different parts of the world representing device/network manufacturers, service providers, academia, and regulators have worked together in 3GPP for over three years to complete the standardization of Release 15 NR, the first 5G standards. With commercial Release 15 NR deployments kicking off in various parts of the world, 3GPP has now turned its focus to the next phase of 5G, 5G Advanced. Over the next several years, 3GPP will build on the foundations laid by Release 15 NR to introduce new functionalities targeted for a wider range of applications and spectrum in Release 16/17 NR.

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