5G NR Radio Interface

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Abstract

This paper presents an overview of the 5G NR radio interface as specified by 3GPP. Specifically, the paper covers 5G NR in IMT2020 context, key design criteria and requirements, fundamental technology components of 5G NR, RF requirements and spectrum bands, Radio Resource Management and Link Monitoring and co-existence/sharing of 5G NR and LTE.

Keywords: 5G, NR, cellular radio technology, 3GPP, IMT2020, RRM, spectrum bands, mMTC, URLLC, eMBB.

1 3GPP 5G NR Standards Process in the Context of IMT2020

Mobile communications have become an integral part of daily life across the world: cellular technology developments are changing the society to a

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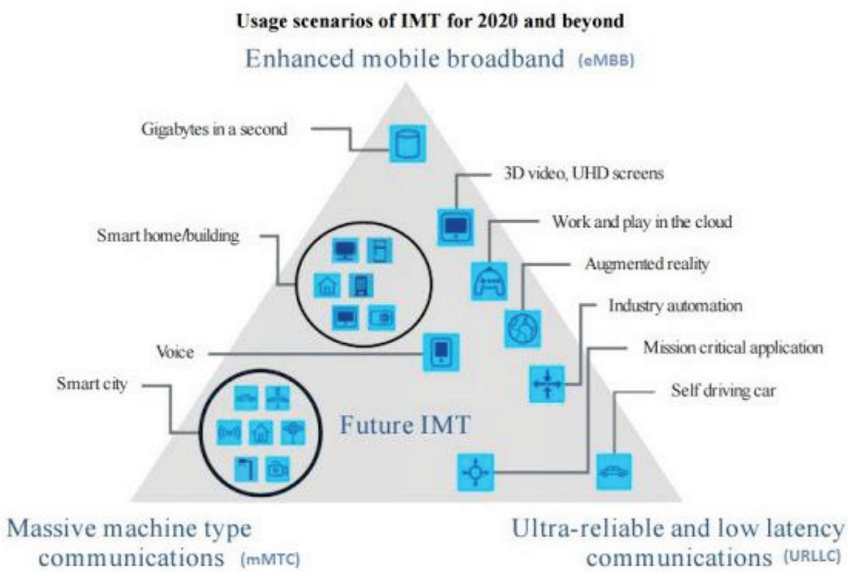

Figure 1 5G use case landscape.

fully connected world. Cellular technology evolution has reached the 5th generation, 5G networks are expected to be the predominant choice for communications in 2020 and beyond. To this end, back in 2015 ITU-R established the 5G vision and described it in Recommendation ITU-R M.2083. In essence, 5G technology is expected to be applied to a diverse range of usage scenarios including enhanced mobile broadband (eMBB), massive machine type communication (mMTC) and ultra-reliable and low latency communication (URLLC) – see Figure 1.

Starting with an all-encompassing workshop in September of 2015 3GPP has set out to deliver the technology standards to fulfil the communication needs of the next 20 years. Roadmaps and plans were put in place to deliver on an extremely ambitious schedule, see Figure 2.

3GPP is set out to complete the first version of 5G technology standards in June 2018 (with ASN.1 protocol freeze in September 2018). As an intermediate step 3GPP is delivering an intermediate set of 5G standards 6 months ahead of this schedule to meet the high industry demand for rapid availability of 5G-based Mobile Broadband capacity expansion.

It shall be noted, however, that the realization of the full 5G vision will take several evolutionary steps after the initial launch, and will take 3GPP several more standards releases over the coming decade to deliver all the capabilities required.

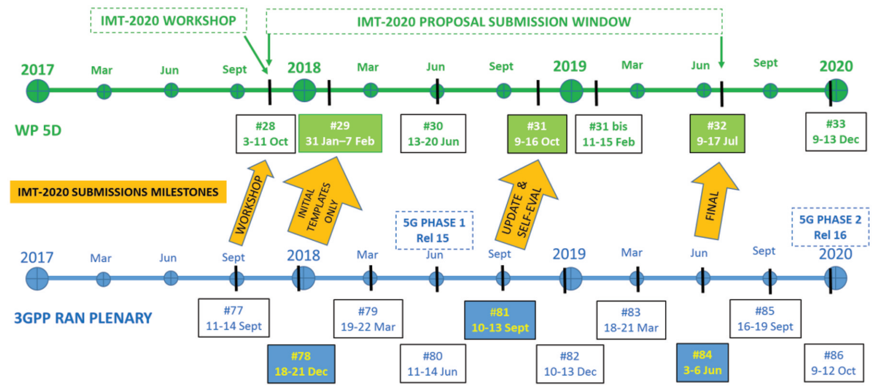

Figure 2 Overall time plan for 3GPP technology submissions to IMT2020.

2 Design Criteria and Requirements

The key capabilities of a 5G network are defined in ITU-R as shown in Figure 3.

For Enhanced Mobile Broadband (eMBB) usage scenario, the 100 Mbps user experience data rate and area traffic capacity of 10 Mbps/m2 are expected with the support of large bandwidth and 3 times spectral efficiency improvement as compared to 4G systems. These capabilities should be reached while retaining sustainable energy consumption levels. Mobility is also important and should be improved to support devices moving with speeds as high as 500 km/h.

For Massive Machine Type Communications (mMTC) usage scenario, connection density is expected to reach 1,000,000 devices per km^2 due to the demand of connecting vast number of devices over the next decade.

For Ultra Reliable Low Latency (URLLC) usage scenario, the 1 ms latency with very high (99.999%) reliability has been put forward as a design goal.

To reach the 5G vision defined by ITU-R, 3GPP further studied the deployment scenarios and the related requirements associated with the three usage scenarios. The 3GPP requirements complement the ITU requirements defining relevant metrics to the usage scenario. For example, 3GPP also defines targets of low power consumption and deep coverage for mMTC usage scenario.

In general, both ITU and 3GPP requirements imply that 5G networks should deliver diverse capabilities depending on the type of services and applications. Furthermore, the unforeseen future services should be supported in a smooth manner. Meanwhile, these capabilities should be provided subject to the constraint of spectrum, energy consumption, and affordable cost. Therefore, 5G needs to be flexible with a unified radio interface of high

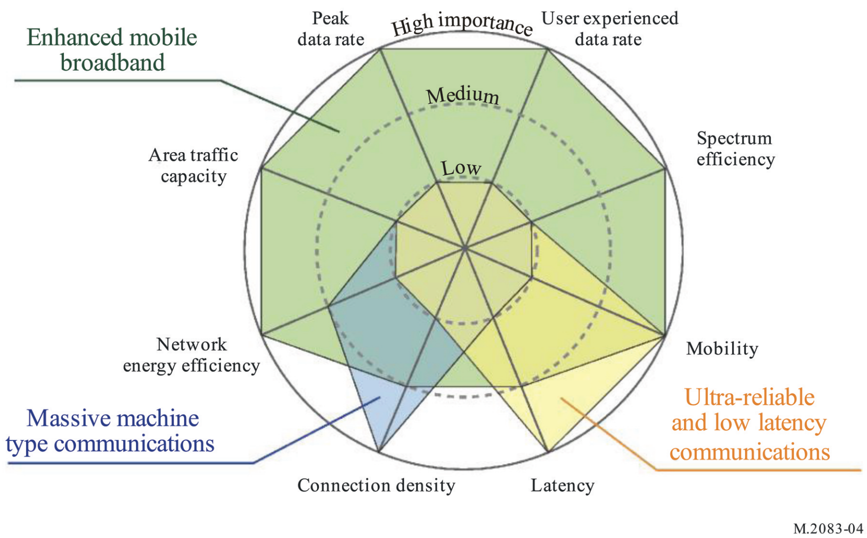

Figure 3 Key capabilities of 5G networks.

spectrum utilization efficiency as well as energy efficiency. All this calls for a higher degree of innovation on the different technical components of the 5G system. In terms of cellular radio technology 3GPP has answered the call by designing a new radio interface, called NR.

3 5G NR Radio Interface Technology Components

3.1 Physical Layer Structure

In NR, similar to LTE, a radio frame is fixed to be 10 ms, which consists of 10 subframes each of 1ms. However, different from LTE which has a fixed subcarrier spacing (SCS) for 15 kHz, NR supports scalable numerology for more flexible deployments covering a wide range of services and carrier frequencies. In particular, NR supports the following SCSs (f_0):

- $f_0 = 15$ kHz $* 2^m$, where $m = \{0, 1, 2, 3, 4\}$, i.e., $f_0 = \{15, 30, 60, 120, 240\}$ kHz

Note that 15 kHz, 30 kHz and 60 kHz are applicable to carrier frequencies of 6 GHz of lower (sub-6), where 60 kHz, 120 kHz and 240 kHz are applicable to above 6 GHz carrier frequencies.

The subframe duration of 1ms is based on 15 kHz reference numerology with 14 symbols per subframe for the case of normal cyclic prefix (NCP). It is

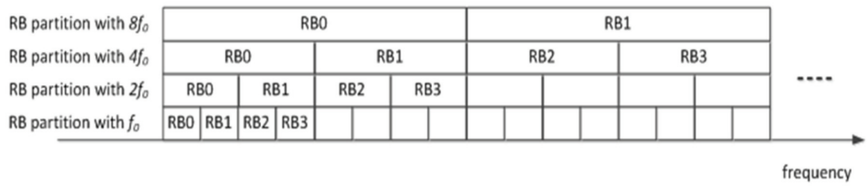

Figure 4 Illustration of nested RB-structure across numerologies.

also called a slot for 15 kHz SCS. For other SCSs, 14-symbol per slot is always assumed for NCP (except for 240 kHz, where 28-symbol per slot is assumed for NCP), resulting in SCS-dependent slot duration and nested slot structure across numerologies. As an example, a 30 kHz SCS has a slot duration of 0.5 ms, which can be mapped to two slots (each of 0.25 ms) for a 60 kHz SCS. Moreover, frequency-alignment within the channel is also achieved via nested resource blocks (or RBs, each of 12 frequency-consecutive tones) structure across numerologies, as illustrated below. Such nested slot structure and nested RB-structure facilitates multiplexing of different numerologies in a same cell or for a same UE, see Figure 4.

In addition to slots, NR frame structure supports *slot aggregation* and *mini-slots*. Slot aggregation refers to the case when a transmission can span two or more slots in order to achieve improved coverage and/or reduced overhead. Mini-slots (also known as *non-slot-based scheduling*) refer to the case when a transmission can span a number of symbols significantly less than the number of symbols in a slot (14), e.g., as small as 1-symbol. This provides more flexible resource management for a cell and possibilities to achieve low latency (LL), which when combined with ultra-reliability (UR) readily brings URLLC (URLL communications) services.

Flexible slot structure is one essential component for NR, not only for flexible resource management for current deployments but also necessary for future compatibility. To that end, NR supports up to two DL/UL switching points in a slot, particularly:

- Zero switching point within a slot, which implies 14 'DL' symbols, 14 'flexible' symbols, or 14 'UL' symbols. The flexible symbols can be dynamically and UE-specifically indicated for DL or UL symbols based on actual need.
- One switching point within a slot, which starts with zero or more DL symbols and ends with zero or more UL symbols, with necessary 'flexible' symbols in between.

- Two switching points within a slot, where the first (or second) 7 symbols start with zero or more DL symbols and ends with at least one UL symbol at symbol #6, with zero or more 'flexible' symbols in between.

The maximum channel bandwidth supported by NR is 100 MHz for sub-6 and 400 MHz otherwise. Note that the maximum supported UL/DL channel bandwidth in the same band can be different. The minimum channel bandwidth is 5 MHz for sub-6 and 50 MHz otherwise. New maximum channel bandwidths, if necessary, can be added in future releases as NR is designed to ensure forward compatibility. The channel bandwidth of a cell that can be utilized for communications is as high as 98%.

3.2 Initial Access and Mobility

NR supports up to 1008 physical cell identities, twice as many as that of LTE. It follows a similar two-step cell identification procedure as in LTE, via detection of primary synchronization signal (PSS) and secondary synchronization signal (SSS). Time synchronization (in terms of symbol-level and slot-level) and frequency synchronization are also realized via PSS/SSS.

Master information block (MIB) of a cell is detected via a channel called primary broadcast channel (PBCH). System frame number (SFN) synchronization is acquired accordingly. In addition, PBCH demodulation enables reception of subsequent physical downlink control channels (PDCCH) and physical downlink shared channels (PDSCH), which schedule remaining minimum system information (RMSI), other system information (OSI), and paging messages.

For initial access, an essential building block called SS Block (SSB) is defined. A 4-symbol SSB consists of a 1-symbol PSS, a 1-symbol SSS, and a 2-symbol (and a bit extra) PBCH, as illustrated in Figure 5. The SCS for PSS/SSS depends on different frequency ranges, particularly:

- For sub-6 GHz: 15 kHz or 30 kHz for SSB
- For above-6 GHz: 120 kHz or 240 kHz for SSB

A SS burst set is comprised of a set of SS blocks (see Figure 5), each of potentially different beams necessary particularly for high carrier frequencies for initial access. Each SS burst set is limited to a 5 ms window regardless of the periodicity, which can be {5, 10, 20, 40, 80, 160} ms as indicated in RMSI, configured for SS burst sets. For initial cell selection, the SS burst set periodicity is default at 20 ms for all frequency range. Both the number of SS

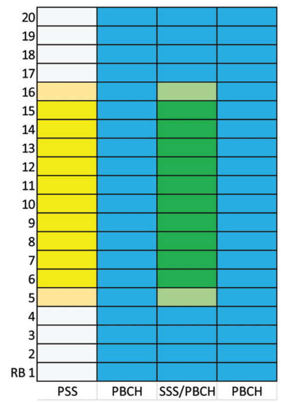

Figure 5 Illustration of SS block.

blocks (L) within a SS burst set and the location of SS burst set within the 5 ms window depend on the carrier frequency range. As an example,

- For carrier frequency range up to 3 GHz, $L = 4$
- For carrier frequency range from 3 GHz to 6 GHz, $L = 8$
- For carrier frequency range from 6 GHz to 52.6 GHz, $L = 64$

The number of possible PSS sequences is 3, each of a frequency-domain BPSK length-127 M-sequence. SSS sequence also has a length of 127 and it is a scrambled M-sequence. Both PSS and SSS are mapped to 127 consecutive tones within 12 RBs, where among the 144 tones, 8 tones and 9 tones are reserved on the two sides respectively. A 56-bit payload PBCH (including CRC) is mapped to a total of 240 tones. PBCH has a transmit-time-interval (TTI) of 80 ms. In other words, PBCH contents, including information such as SFN, SSB index, raster offset, default DL numerology, RMSI configuration, DM-RS location, etc., are updated every 80 ms. PSS, SSS, and PBCH are all one port only and share the same port.

PDSCH, scheduled by PDCCH, carries RMSI. The configuration of PDCCH for RMSI is provided by PBCH. The COntrol REsource SET (CORESET) configuration for RMSI is associated with a SS block in a SSB burst set. A one-bit information field in PBCH signals the SCS of RMSI, as well as OSI and other messages in random access procedures for initial access. The possible SCS combinations are:

- $\{$SSB SCS, RMSI SCS$\} = \{\{15, 15\}, \{15, 30\}, \{30, 15\}, \{30, 30\}, \{120, 60\}, \{120, 120\}, \{240, 60\}, \{240, 120\}\}$ kHz

The RMSI PDCCH monitoring window is associated with an SSB and recurs periodically. The TTI for RMSI is 160 ms. Multiplexing of SSB and RMSI can be TDM or FDM. However, the pattern of multiplexing depends on and is restricted for a given SCS combination. As an example, for a $\{30, 30\}$ SCS combination, only TDM pattern is allowed.

Similarly, for OSI, it is also carried by PDSCH, which is scheduled by PDCCH. For broadcast OSI CORESET configuration, the same configuration for RMSI CORESET is reused. The monitoring window configuration for OSI, e.g., time offset, duration, periodicity, etc., is explicitly signalled in a corresponding RMSI. In addition, for connected mode UEs, non-broadcast and on-demand (i.e., dedicated) OSI transmission is supported.

For paging, its subcarrier spacing of control and data channels is the same as that of RMSI. A UE is explicitly signalled paging occasion configuration, e.g., time offset, duration, periodicity, etc. Paging CORESET reuses the same configuration for RMSI CORESET. Two paging mechanisms are supported:

- Paging is done via PDSCH scheduled PDCCH, both channels in the same slot
- Paging is done via PDCCH only, useful for short paging messages

Random access (RA) enables a UE to access a cell, and it is performed by a 4-step procedure, similar to LTE:

- Message 1 (RA channel preamble): UE → gNB
    - It is based on Zadoff-Chu sequence with two sequence lengths, called long sequences and short sequences
    - Both contention-based RA (CBRA) and contention-free based RA (CFRA) are supported
    - One or multiple SSBs can be mapped to one PRACH transmission occasion
- Message 2 (Random access response or RAR): gNB → UE
    - It carriers information such as TA commands, temporary ID, etc.
- Message 3 (first PUSCH transmission): UE → gNB
    - It is scheduled by the UL grant in RAR
- Message 4 (PDCCH/PDSCH): gNB → UE

Radio resource management (RRM) in NR is based on measurements of SSB or CSI-RS, and can be reported with metrics such as reference signal received power (RSRP), reference signal received quality (RSRQ), and signal-to-interference-noise-ratio (SINR). Similarly, for radio link monitoring (RLM), both SS block based RLM and CSI-RS based RLM are supported. A hypothetical PDCCH block-error-rate (based on RLM-RS SINR) is the metric for determining in-sync (IS) and out-of-sync (OOS) with the cell.

3.3 Channel Coding and Modulation

In NR, new channel coding mechanism were chosen (LTE has used turbo codes and tail-biting convolutional codes).

NR uses LDPC codes for data which is transmitted on the physical downlink and uplink shared channels (PDSCH and PUSCH). Polar codes are used for downlink control information (DCI) that is transmitted on the physical downlink control channel (PDCCH) and for the master information block (MIB) which is transmitted on the physical broadcast channel (PBCH). Polar codes, repetition codes, simplex codes or the LTE Reed-Muller code are used for uplink control information (UCI) that is transmitted on the physical uplink control channel (PUCCH) or the PUSCH.

In general, LDPC codes are defined by a sparse parity check matrix which defines a set of linear equations (parity checks) that must be satisfied by any valid codeword. A parity check matrix is defined by a base graph along with a lifting size and cyclic shifts for the edges of the graph. For NR, two base graphs are defined, along with eight sets of lifting sizes which cover a wide range of information block sizes and code rates. For a given base graph, eight sets of parity check matrices are defined by providing eight different sets of cyclic shifts, one for each set of lifting sizes. The choice of base graph depends on the size and code rate of the initial transmission.

The operations applied to data that is LDPC-coded and transmitted on the physical downlink and uplink shared channels (PDSCH and PUSCH) are described below. Data is sent in units called transport blocks (TB) to which a CRC is attached so that the receiver may detect whether the TB was received correctly. The CRC is 24 bits when the TB size is larger than 3824 bits, and a 16 bit CRC is used in all other cases. The transport blocks (including the 24 bit CRC) are segmented into multiple code blocks when base graph 1 is used with a transport block size greater than 8424 bits or when base graph 2 is used with a transport block size greater than 3824 bits. When code block segmentation is applied, each code block is appended with its own 24-bit CRC. When no segmentation is used, the code block is the transport block. The one or more code blocks are then individually coded using the LDPC code. Rate matching is performed for each code block. Rate matching is a process that adjusts the number of coded bits of the code blocks to fit the resources available for the transport blocks. The available resources are dependent on the resources being used for other purposes including reference signals, system information, control channels and reserved resources. The coded bits selected in the rate-matching process, both for initial transmissions and re-transmissions, are chosen from a circular buffer into which the LDPC encoder output is written. Incremental redundancy is employed for Hybrid-ARQ re-transmissions by selecting different sets of coded bits for different transmissions. This is achieved by using different starting points in the circular buffer to generate the different sets of consecutive coded bits. After rate matching, bit-level interleaving is applied to each code block prior. The code blocks are then concatenated, scrambled and then modulated.

Polar codes strive to transform a set of noisy channels into noiseless and completely noisy synthetic channels when the code size approaches infinity. List decoding is used for decoding of polar codes with assistance from the CRC, and from additional parity check bits for uplink control, to choose candidates in the list.

For the DCI transmitted on the PDCCH, a block of 24 CRC bits is distributed among the DCI bits using an inter-leaver. The distributed CRC allows list decoding in the UE to potentially terminate early. Scrambling of the CRC bits at the end with the RNTI enables the UE to determine if the message is intended for it. Polar coding is used to generate the coded bits which are then rate matched and modulated. Rate-matching is performed using a circular buffer by using shortening, puncturing or repetition of the coded bits. The maximum polar code size is 512 bits. The polar code defined for PDCCH is reused for PBCH with a fixed input and output size where a 24-bit CRC is attached to the 32-bit MIB content before Polar encoding.

For uplink control information (UCI), repetition coding, (3,2) simplex coding or LTE Reed-Muller coding is used if the UCI length is 1 bit, 2 bits or 3–11 bits respectively. When the UCI length is 12–19 bits, polar coding is used with a 6-bit CRC attached at the end and three additional parity check bits inserted to assist with list decoding. When the UCI length is greater than 19 bits, polar coding is used with a 11-bit CRC attached at the end and a part of the CRC being useable for assistance to the list decoder. Rate-matching and bit-level interleaving are then performed. The maximum polar code size for UCI is 1024 bits. UCI of 360 bits or greater may be evenly segmented into two blocks which are individually encoded as described above, interleaved and concatenated prior to modulation.

In NR, QPSK, 16-QAM, 64-QAM and 256-QAM modulations are supported for the PDSCH and PUSCH. In addition, $\pi/2$-BPSK, where a $\pi/2$ shift is applied to successive modulated symbols, is supported when DFT-spread OFDM is used in the uplink. The PDCCH and the PBCH use QPSK. The PUCCH uses sequence selection, BPSK or QPSK depending on the PUCCH format and the number of bits with $\pi/2$-BPSK available as a configurable option.

3.4 Scheduling and Hybrid ARQ

For NR, the physical downlink control channel (PDCCH) is used for dynamic scheduling to deliver downlink control information (DCI), which includes the information required for the UE to process the scheduled data. For downlink data scheduling, the scheduling DCI also includes radio resource/timing information of the Hybrid ARQ-acknowledgement (HARQ-ACK) feedback. After receiving the downlink data, the UE reports its HARQ-ACK by the physical uplink control channel (PUCCH) at the radio resource/timing where the scheduling DCI indicates. For uplink data scheduling, there is no specific channel to inform HARQ-ACK. Once gNB fails to decode the uplink data, it schedules re-transmission of the uplink data, while if gNB successfully decodes the uplink data, it can schedule new uplink transmission data.

For NR, one of the key differences from LTE is its highly symmetric properties in the downlink and uplink scheduling and HARQ. In LTE, radio resource allocation schemes are different between downlink and uplink due to different multi access schemes, and downlink HARQ is basically asynchronous and adaptive while uplink HARQ is synchronous and non-adaptive. On the other hand, in NR, almost all scheduling and HARQ mechanisms are common between downlink and uplink such as: (1) radio resource allocation schemes, (2) Rank/modulation/coding adaptations, and (3) asynchronous and adaptive Hybrid ARQ.

Another key difference from LTE is its high flexibility in the time-domain. In LTE, time-domain radio resources for scheduled data and/or HARQ-feedback are basically not informed by the scheduling DCI, and it is determined by the frame structure and the UL-DL configuration. In NR, as shown in Figure 6, the scheduling DCI basically includes time-domain information of the scheduled data (and time-domain information of HARQ-ACK feedback in case of downlink) where the time-domain information here refers to the combination of the scheduled slot, the start symbol position, and the

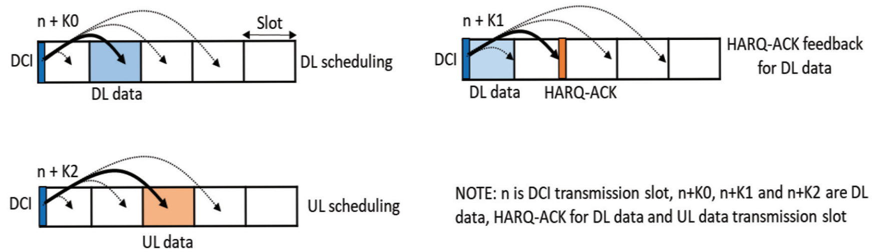

Figure 6 Dynamic radio resource allocation timing for NR scheduling and HARQ.

transmission duration. By this, NR can easily realize various operations e.g., full/half duplex FDD, dynamic/semi-static TDD, and unlicensed operation *etc*. and satisfy different UE's requirements, e.g., lower latency, higher data rates. See Figure 6.

Regarding HARQ-ACK feedback for downlink data, and for uplink data transmission, UE requires processing time. In LTE, the minimum processing time is 3 ms. NR significantly reduces this processing time; it is subcarrier-spacing and demodulation reference signal mapping dependent, but overall the minimum processing time for downlink data is 0.2–1 ms and for uplink data is 0.3–0.8 ms. Together with enabling shortened data transmission duration, NR can realize lower U-plane latency compared to LTE.

3.5 MIMO

The use of multi-antenna technology in NR is focused on two objectives. First objective is to ensure sufficient coverage for NR deployment in over-6 GHz spectrum where propagation loss over wireless channels is significantly higher than that of sub-6 GHz spectrum. For example, compared to 2$\sim$3 GHz where many of today's LTE networks are deployed, transmission over 28 GHz spectrum is expected to experience signal attenuation that is 100 times stronger. The second objective is to achieve a spectral efficiency that is 3 times that of LTE. This spectral efficiency improvement is especially important for sub-6 GHz spectrum since NR needs to compete against LTE in this spectrum.

Overcoming the large propagation loss is achieved in NR with multi-beam operation where the transmitter and receiver utilize multiple highly directional beams using a large number of antenna elements. At a given time instance, data transmission to or from a base station is made using one of the multiple beams that can provide sufficient signal quality. Support for multi-beam operation in NR includes beam quality measurement, beam quality reporting, beam assignment, and recovery mechanism in case the assigned beam quality is not good enough. NR provides support for multi-beam operation at every stage of the radio operation: initial/random access, paging, data/control transmission/reception, and mobility handling.

Improving the spectral efficiency over LTE is achieved in NR with the utilization of additional antenna ports in combination with an accurate channel status information (CSI). For example, compared to basic LTE which supports up to 4 transmit antenna ports are supported for a base station and 2 receive antennas are mandated for a terminal, NR supports up to 32 transmit antenna ports for a base station and 4 receive antennas are mandated for a terminal (in certain frequency bands).

An accurate CSI is essential in order for the base station to effectively separate the transmission signals to or from multiple terminals in the spatial domain. For the uplink, sounding reference signal (SRS) can be used for CSI acquisition. For the downlink of time-division duplexing (TDD) bands, when downlink-uplink channel reciprocity is available, channel measurement via UL signals can be used. For the downlink of frequency-division duplexing (FDD) bands or TDD bands where channel reciprocity is not available, NR supports efficient CSI reporting with high-resolution spatial channel information well beyond what LTE supports. High-resolution spatial channel information in NR is provided via a two-stage high-resolution precoding where the first stage selects a basis subset, and the second stage selects a set of coefficients for approximating a channel eigenvector with a linear combination of the basis subset.

4 RF Requirements and Spectrum Bands

NR brings new spectrum opportunities which allow the operating bands to extend up to 52.6 GHz in Release 15. Considering different testing methods to verify the Radio Frequency (RF) and Radio Resource Management (RRM) requirements in different frequency range, i.e., Over the Air (OTA) testing or conductive testing, two frequency ranges are categorized, i.e., Frequency Range 1 (FR1) 450 MHz–6 GHz and Frequency Range 2 (FR2) 24.25 GHz–52.6 GHz.

For operating bands within FR1 and FR2, prefix “n” with Arabic numerals is used to label the NR bands to differentiate the LTE bands labelled in Arabic numerals and UTRA bands labelled in Roman numerals. In FR1, prefix “n” with the same LTE band number are used for NR band with exactly same frequency range as LTE band. In addition to these bands, the range of

NR Band	SCS kHz	10 MHz	15 MHz	20 MHz	40 MHz	50 MHz	60 MHz	80 MHz	100 MHz
n77	15	Yes	Yes	Yes	Yes	Yes			
	30	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	60	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Figure 7 NR bands, sub-carrier spacing, channel bandwidth.

n65∼n256 and range n257–n512 are reserved for new bands in FR1 and FR2 respectively.

For each operating band, limited number of channel bandwidth has been specified for each subcarrier spacing (SCS). Taking UE channel bandwidth for Band n77 (TDD band with frequency range 3300 MHz – 4200 MHz) as example, the UE channel bandwidth is defined in a table manner in 3GPP specification. In the table, "Yes" indicates whether the channel bandwidth is supported for certain SCS of certain band. See Figure 7.

For UE channel bandwidth in Release 15, it is further specified that all channel bandwidth listed in current version of specification shall be mandatory supported by UE with a single component carrier in FR1, and all channel bandwidth below 200 MHz shall be mandatory supported by UE with a single component carrier in FR2.

To be noted, for some operating band in FR1 (n77 and n78 in current version of specification), additional channel bandwidth comparing with UE channel bandwidth, i.e., 70 MHz and 90 MHz are specified for BS channel bandwidth to allow more flexible deployment scenario.

More than 90% spectrum utilization has been specified in NR (except certain SCS) as maximum transmission configuration for each SCS and each channel bandwidth in implementation agonistic manner. In order to meet the relative emission requirements, the minimum guard band for each UE channel bandwidth and SCS has been also defined.

To locate the frequency position of RF channel and synchronization block, both channel raster and synchronization raster have been numbered as NR Absolute Radio Frequency Channel Number (NR-ARFCN) and Global Synchronization Channel Number (GSCN). To further assist the UE to find frequency position of RF channel and synchronization block in certain band, the applicable NR-ARFCN and GSCN are specified as the range of NR-ARFCH/GSCN and different step size for each operating band.

For FR2 NR UE and some NR BS types, due to highly integrate antenna implementations, physical conductive testing interface may not exist anymore. To specify the radiated requirements has to consider both RF performance and also the test methods. Overall, directional requirements, e.g., EIRP/EIS and non-directional requirements, e.g., TRP have been specified for corresponding RF requirements for UE and BS.

For UE RF requirements, not only the requirements for UE operating with single NR carrier but also the requirements for UE operating with Carrier Aggregation (CA), E-UTRAN-NR Dual Connectivity (EN-DC) and Supplementary uplink (SUL) are specified. For EN-DC operation, different set of requirements have been specified for intra-band EN-DC configuration and inter-band EN-DC configuration.

Different sets of requirements have been specified for different type BSs. In Rel-15, according to the applicable requirements, i.e., conductive, OTA or Hybrid, and also operating frequency range, four BS types are specified which are BS type 1-C, BS type 1-H, BS type 1-O and BS type 2-O. For example, BS type 1-C is defined as BS operating at FR1 with requirements set consisting of conductive requirements.

5 Radio Resource Management (RRM) and Demodulation

The new synchronization signals for initial access and mobility are designed in 5G NR to provide more flexibility and better trade-off between the system performance and UE power consumption for measurement. 5G NR supports both standalone (SA) and non-standalone (NSA including LTE-NR DC). Compared to LTE, multiple numerologies, the wider channel bandwidths, the more flexible uplink-downlink slot configurations, and the wider frequency ranges covering sub-6 GHz (Frequency range 1, FR1 for short) and mmWave (Frequency range 2, FR2 for short) are supported. The 5G NR RRM/RLM and demodulation performance requirements have been specified considering all these aspects.

5.1 Overview of RRM Core Requirements

The SS/PBCH block (SSB) burst consists of multiple SSB-s, which are associated with the different SSB indices and potentially with the different transmission beams. Besides, the CSI-RS signals can also be configured for beam management and measurement. The SSB-based measurement timing configuration (SMTC) with a certain duration and periodicity is used to restrict the UE measurement on the certain resources to reduce the UE power consumptions. Within SMTC period and on the configured SSB and/or CSI-RS, UE will conduct the RLM/RRM measurement.

For LTE-NR DC the initial access and mobility are done on LTE PCell (Primary Cell). NR CC will be added or released as SCell (Secondary Cell), while in SA mode all the operations will be done directly on NR PCell. Thus, the RRM requirements for LTE-NR DC (NSA) and SA are partially different. Table 1 below summarizes the RRM requirements. Those requirements guarantee the initial access and mobility performance for the LTE-NR DC, Supplemental Uplink (SUP), and NR-NR Carrier Aggregation (CA).

Table 1 RRM Core requirements for E-UTRA-NR DC (NSA) and SA

Core Requirements	SA and NSA Common	NSA Specific	SA Specific
RRC_IDLE state mobility	–	–	Cell selection
	–	–	Cell re-selection and interruption in paging reception
RRC_INACTIVE	–	–	Cell re-selection
	–	–	RRC_INACTIVE mobility control
RRC Connection Mobility Control	–	–	Handover
	–	–	RRC Re-establishment
	–	Random access for NR PSCell	Random access for NR PCell
	–		RRC connection release with redirection
Timing	UE transmit timing	–	–
	UE timer accuracy	–	–
	timing advance	–	–
	Cell phase synchronization accuracy for NR TDD BS	–	–
	–	Maximum transmission timing difference (MTTD) for E-UTRA-NR DC	–

(*Continued*)

Table 1 Continued

Core Requirements	SA and NSA Common	NSA Specific	SA Specific
	–	Maximum receive timing difference (MRTD) for E-UTRA-NR DC	Maximum receive timing difference (MRTD) for NR CA
Signal characteristics	RLM	–	–
	–	Interruption on NR PSCell due to the operations for E-UTRA PCell/SCell or UL carrier RRC reconfiguration	–
	–	Interruption on E-UTRA PCell/SCell due to the operation for NR PSCell/SCell or UL carrier RRC reconfiguration	–
	–	Activation/deactivation SCell in SCG for E-UTRA-NR DC	–
	UE UL carrier RRC reconfiguration delay	–	–
RRM measurement	–	Measurement capability for E-UTRA-NR DC	Measurement capability for SA NR
	Intra-frequency measurement with gap	–	–
	Intra-frequency measurement without gap	–	–
	Inter-frequency measurement	–	–
	–	–	Inter-RAT measurement

5.2 Definition of Intra-Frequency and Inter-Frequency Measurement

The first step for NR RRM is the definition of inter-frequency and intra-frequency measurement. Unlike LTE NR may utilize the different numerologies and configure the frequency location of SSB in a more flexible way. Thus, the definitions of inter-frequency and intra-frequency measurement for NR are different from LTE. For LTE, if the center frequency between the serving cell and the targeting cell is the same, the measurement can be viewed as intra-frequency measurement. Otherwise, it is viewed as the inter-frequency. For NR, a measurement is defined as a SSB-s based intra-frequency measurement provided the centre frequency of the SSB of the serving cell indicated for measurement and the centre frequency of the SSB of the neighbor cell are the same, and the subcarrier spacing of the two SSB-s are also the same.

5.3 Measurement Capability

In contrast to LTE the detected beam (SSB) number as well as the frequency layer number and cell number will be defined for NR capability by taking into account the support of multiple Tx beams. Besides, because there is difference between FR1 RF and FR2 RF chains, e.g., separate RF chains will be used for FR1 and FR2, and the analog Rx beamforming will be conducted for FR2, the capabilities for FR1 and FR2 are defined separately. When deriving the concrete numbers of carriers, cells and SSBs, the trade-off between the high capability and UE complexity is considered, and it is desirable not to increase NR UE capability too much compared to LTE capability.

The LTE-NR DC capable UE is required to measure the frequency layers of NR, LTE FDD, LTE TDD, UTRA FDD, UTRA TDD and GSM. But in the first version of the NR specifications (Release 15) a Standalone (SA) NR UE is required to measure LTE and NR only.

5.4 Measurement Gap

For measurement gap design there are totally 24 gap patterns defined to match the different SMTC durations, which correspond to different SSB burst lengths caused by different numerologies and different uplink-downlink transmission configurations. Given that different SCS-s are supported in FR1 and FR2, the specified lengths of SMTC between FR1 and FR2 are different. Thus, the different gap patterns apply to FR1 (roughly pattern #0$\sim$11) and FR2 (roughly pattern #12$\sim$23) separately.

As explained above, it is expected to be common that the separate RF chains is utilized for FR1 and FR2. Hence, the gap pattern for NR could be configured per UE or per-RF range.

In addition, the gap sharing between intra-frequency measurement with gap and inter-frequency measurement is specified to keep the lower UE power consumption. And the measurement gap timing advance mechanism will be utilized to improve the measurement performance for the case where the measurement gap and SMTC window duration are not aligned.

5.5 Measurement Requirements

The measurement requirements for NR include SSB based measurements and CSI-RS based measurements.

For SSB based measurement, UE will conduct intra-frequency/inter-frequency RSRP, RSRQ and RS-SINR measurement with or without gap. For CSI-RS based measurement, the CSI-RS based beam measurement will be conducted and UE will report the physical layer RSRP. The CSI-RS based RSRP, RSRQ and RS-SINR are also supported.

From measurement perspective, FR2 UE will utilize the analog and/or digital receiver beamforming for the measurement. Hence, longer measurement time is needed for FR2 to allow that the FR2 UE sweeps the whole space. The typical intra-frequency measurement period for FR1 consists of cell identification time, SSB timing index detection time and RSRP/RSRQ measurement period. At the same time, an FR2 UE is required to decode PBCH payload and thus the longer time is needed for intra-frequency measurement. Hence, the measurement requirements are specified for FR1 and FR2 separately.

The period of inter-frequency or intra-frequency measurement with gaps will be scaled by the gap periodicity based on the intra-frequency measurement period. The requirements in DRX mode will be derived by using the similar approach as for LTE.

5.6 Radio Link Monitoring (RLM)

There are two sets of target Block Error Rates (BLER) for NR RLM measurement: one corresponding to generic data service and one corresponding to voice service. Accordingly, two sets of configurations are specified. Both SSB-based RLM and CSI-RS based RLM are specified.

For NR the measurement period (for Signal-to-Noise Ratio (SNR)) is defined for each RLM-RS resource.

It is specified that a UE shall be able to monitor up to 2 RLM-RS resources for frequency range equal to or less than 3 GHz, 4 RLM-RS resources for frequency range larger than 3 GHz, and 8 RLM-RS resources for FR2.

5.7 Demodulation Performance Requirements

In NR the demodulation performance requirements will be specified covering single carrier, LTE-NR DC, and NR-NR CA schemes. This includes the baseline uplink-downlink transmission configuration, channel model, the number of Rx and Tx, etc. For UE both 2Rx and 4Rx based demodulation requirements are specified.

6 Coexistence and Sharing of 5G NR and LTE

The success of any new generation of wireless technologies depends on the ability of operators and users to migrate from currently deployed wireless systems to the new system. Each generation of wireless technologies has traditionally been introduced along with new spectrum that is made available for the deployment of that technology. As the number of users using the new technology gradually increases, spectrum can be migrated from the older to the newer technology. However, in the case of 5G NR, an additional constraint is that the new spectrum being considered for NR initially is generally not at low frequencies and therefore does not allow for the same level of coverage as the spectrum in which LTE is currently deployed. Hence, there is a motivation to consider techniques beyond the traditionally provided ability to handover users between older and newer systems. Many deployment options and techniques for system operation are defined as part of NR to achieve efficient coexistence and migration.

Dual connectivity between NR and LTE is a deployment option supported by NR where LTE, deployed typically in a lower frequency band and acting as an anchor carrier, can be used to ensure coverage while NR can be used at higher frequencies, including milli-meter wave frequencies, to provide very high capacity. The NR gNB and LTE eNB may or may not be co-located. While such deployments can allow NR to provide a capacity boost while running in such a non-standalone mode of operation, for a full transition to NR, NR will be deployed to operate in a standalone mode as well where an LTE anchor carrier is not needed. Eventually, it is desirable for NR to be deployed at lower frequencies as well. Given the paucity of spectrum in low frequency bands, providing new spectrum or re-farming LTE spectrum at lower frequency bands is difficult without an adverse effect to current users of LTE. Therefore, a finer granularity in allocation of radio resources between NR and LTE is needed. To achieve this, NR supports a carrier that is overlapped in frequency with LTE.

NR provides the option of only deploying the uplink (either independent or shared with LTE) in the lower frequency band while the downlink continues to operate in a higher frequency band. Another deployment option for NR is to operate a supplementary uplink in addition to a downlink and uplink operating in a higher frequency band. In cases where the UL coverage is the limiting factor at higher frequencies, these deployment options may allow operation of NR with a lower site density. When the UE transmits on two uplink carriers simultaneously, intermodulation distortion can affect the receiver sensitivity on the downlink carrier frequency. To avoid this, NR supports cases where the UE transmits only on one uplink at a time. When a supplementary uplink is used, uplink control and data are always transmitted on the same carrier in a slot with the sounding reference signal (SRS) being the only signal that may be transmitted on a different carrier from data and control in a slot although the transmissions don't occur simultaneously. For initial access, the UE selects between the supplementary uplink and the non-supplementary uplink based on the measured received signal strength on the downlink and a decision threshold that is broadcast by the network.

When the spectrum occupancy of the NR and LTE carriers overlaps, the system must ensure that all the signals and channels necessary for normal operation of both NR and LTE can be received in the downlink. The sharing of time-frequency resources can happen dynamically through scheduling or in a semi-static manner. For example, MBSFN (Multicast-broadcast Single-Frequency Network) subframes can be semi-statically configured in LTE and part of the symbols in the subframes can be used for the NR downlink. The design of NR also allows for forward compatibility with the use of reserved resources that are configurable for specific OFDM symbols, physical resource blocks and subframes. The NR signals and channels operate without the use of these resources. This mechanism could be used to protect signals such as the PSS, SSS and PBCH in LTE during an ongoing NR transmission. NR also is designed to be able to avoid transmissions in the resource elements corresponding to the cell-specific reference signals (CRS) in LTE. For instance, a specific pattern for NR synchronization and PBCH signal with 30 kHz subcarrier spacing is supported in order to avoid collision with LTE CRS symbols. These mechanisms facilitate coexistence of NR and LTE on the same carrier in the downlink.

Coexistence in the uplink is enabled mainly by using the scheduling flexibility integral to NR while minimizing the changes to LTE. When the NR and LTE uplinks are on the same carrier, or on separate carriers but with restrictions that force the UE to only transmit on a single uplink at a time, NR and LTE transmissions must be multiplexed in time. To enable such operation for LTE, UL/DL reference configurations corresponding to one of the existing LTE TDD reference configurations can be reused. Such operation can already be configured for an LTE FDD SCell that is carrier-aggregated with an LTE TDD PCell. For coexistence of NR-LTE these configurations have been extended to the LTE PCell. With this approach, the UE only transmits LTE uplink in the UL subframes defined by the reference configuration while NR can be transmitted in other subframes. For an LTE FDD carrier, it is desirable to ensure that all subframes are useable. For the downlink, this is possible and the HARQ-ACKs are transmitted on the uplink based on the UL/DL reference configuration. For the uplink, while transmissions from a single UE are restricted to a subset of subframes, separate offsets to the UL/DL configuration may be defined for different UEs to improve overall uplink utilization.

7 Summary and Outlook

3GPP have fully committed to delivering technology standards to provide the foundation for the 5G era. This article has described the basic technology components and characteristics of the NR radio interface. It is expected that NR will constitute the foundation for all 5G radio networks in the future, however, LTE will remain to be an integral part of operator networks providing an ever-improving mobile broadband experience.

Whilst initial 5G radio and system specifications are becoming available in 2018 with Release 15, it is expected that the delivery of all technology capabilities fulfilling the entire 5G vision will span over an evolutionary period of several years. 3GPP Release 16, 17 and beyond will continue to add functionality that enables efficient support of an ever wider ranging set of use cases and services.

Abbreviations

BS	Base Station
CORESET	Control Resource Set
E-UTRA	Evolved Universal Terrestrial Radio Access
eMBB	Enhanced Mobile Broadband
FEC	Forward Error Correction
HARQ	Hybrid Automatic Repeat Request
LDPC	Low Density Parity Check
MAC	Medium Access Control
mMTC	Massive Machine Type Communications
MIMO	Multiple Input Multiple Output
NCP	Normal Cyclic prefix
OFDM	Orthogonal Frequency Division Multiplexing
CP	Cyclic Prefix
FDD	Frequency Division Duplex
TDD	Time Division Duplex
PDSCH	Physical Downlink Shared Channel
PDCCH	Physical Downlink Control Channel
PBCH	Physical Broadcast Channel
PRACH	Physical Random Access Channel
PSS	Primary Synchronization Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RB	Resource Block
RRC	Radio Resource Control
RRM	Radio Resource Management
RLC	Radio Link Control
SCS	Sub Carrier Spacing
SSS	Secondary Synchronization Signal
UE	User Equipment
URLLC	Ultra Reliable Low Latency

Biographies

Balazs Bertenyi received an M.Sc. Degree in Computer Science and Telecommunications in 1998 at the Technical University of Budapest.

Balazs joined Nokia in 1998 and started to work on circuit switched mobile switching.

In 1999 he joined the research group on IMS (IP Multimedia Subsystem) and soon started to work in 3GPP standardization on IMS architecture.

- 2000–2003 Representative of Nokia in 3GPP SA2 (Architecture Working Group)
- 2003–2007 Head of delegation for Nokia in 3GPP SA2
- 2007–2011 Chairman of 3GPP SA2
- 2011–2015 Chairman of 3GPP TSG-SA (Technical Specification Group – Services and System Aspects)

In 2015 Balazs moved to the radio standardization group within Nokia to focus on 5G matters. He started attending TSG-RAN in 3GPP in 2015 covering 5G topics.

In 2017 Balazs was elected as Chairman of TSG-RAN for a 2-year term with a potential to be re-elected for one additional term.

Balazs has led various key projects for Nokia on Mobile Broadband architecture and standards strategy.

Satoshi Nagata received his B.E. and M.E. degrees from Tokyo Institute of Technology, Tokyo, Japan, in 2001 and 2003, respectively. In 2003, he joined NTT DOCOMO, INC. He worked for the research and development for wireless access technologies for LTE, LTE-Advanced. He is currently a senior research engineer working for 5G and 3GPP standardization. He had contributed to 3GPP over 10 years, and contributed 3GPP TSG-RAN WG1 as a vice chairman during November 2011 to August 2013, and also contributed as a chairman during August 2013 to August 2017. He is currently a vice chairman of 3GPP TSG-RAN since March 2017.

Havish Koorapaty (Havish.Koorapaty@ericsson.com) received his B.S., M.S., and Ph.D. degrees in Electrical and Computer Engineering from North Carolina State University in 1991, 1993 and 1996 respectively. He has been with Ericsson Research since 1996, where he has worked in the general area of wireless communications systems including cellular and satellite systems. His work spans a wide range of topics including error control coding, location determination and tracking, mobile phone systems engineering, 4G broadband wireless system design, wireless backhaul solutions, energy efficiency, spectrum sharing and small cells. He has over 200 technical papers and patents in these areas. He has represented Ericsson in standardization efforts in the TIA, IEEE and ETSI standardization bodies. Recently, he has worked on LTE evolution and 5G wireless systems. He has been involved in standardization efforts in 3GPP for 5G NR and LTE including serving as the rapporteur for the licensed-assisted access study and work items. He is currently serving as a vice-chairman in 3GPP RAN1.

Xutao Zhou received his Master Degree in Telecommunications form University of Warwick, UK. Mr. Zhou has been employed with Samsung Research China Beijing in 2007 and has been working in standard team, focusing on standardization of mobile communications. Mr. Zhou has been elected as 3GPP RAN4 Chairman in 2015. Since then, Mr. Zhou has been chairing the 3GPP RAN4 meetings for defining the radio frequency requirements for 5G NR and LTE.

Wanshi Chen is currently 3GPP TSG RAN1 Chairman, where under this position, he has successfully managed a wide range of 3GPP TRG RAN1 Long Term Evolution (LTE) and New Radio (NR) sessions. He has over 18 years of experiences in telecommunications in leading telecom companies including operators, infrastructure vendors, and chipset vendors. He has been with Qualcomm since 2006 and is responsible for LTE and NR research, design, and standardization. From 2000 to 2006, he was with Ericsson for 3GPP2 related system design, integration, and standardization. He also worked for China Mobile between 1996 and 1997 for wireless network maintenance and optimization. He received a Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA.

Younsun Kim received B.S. and M.S. degrees in electronic engineering from Yonsei University, and his Ph.D. degree in electrical engineering from the University of Washington, in 1996, 1999, and 2009, respectively. He joined Samsung Electronics in 1999 and has since worked on the physical layer standardization of cdma2000, HRPD, LTE, and recently NR. Currently, he is serving as the vice-chairman of 3GPP RAN1(physical layer) working group.

Xizeng Dai works with Huawei Technologies Co. Ltd since 2008. From October 2008 he began attending 3GPP RAN WG4 meeting as the regular delegate and made contributions to LTE demodulation and RRM topics from Release 8 onwards. Now he is the Vice Chairman of 3GPP RAN WG4 and chaired the RRM and performance session covering NR and LTE topics. He was elected as Vice Chairman in August 2015 and re-elected in August 2017 for the second term. He received his Ph.D of Electrical engineering from Tsinghua University in 2008. He received his MSEE from China Academy of Telecommunication Technology in 2004 and during that period worked on IS-95 and CDMA2000 system development.

Xiaodong XU is a Principal Researcher with CMCC. He has spent more than 10 years working on 3GPP standardization and LTE field network, ranging from physical layer design, higher layer design, and cooperative networking among 2G&3G&4G. And now, he mainly focuses on 3GPP's 5G technology. He is currently serving as the vice chairman of the 3GPP TSG RAN that is responsible for the specification of radio interface for 2G and onwards. Xiaodong XU received his PhD degree in communication and information system from the Southeast University, Nanjing, China, in 2007.