NR: The New 5G Radio Access Technology

Stefan Parkvall, Erik Dahlman, Anders Furuskär, and Mattias Frenne

Abstract

This article provides an overview of the technology components and capabilities of the New Radio (NR) radio interface standard currently under development by 3GPP. NR will enable new use cases, requiring further enhanced data rates, latency, coverage, capacity, and reliability. This needs to be accomplished with improved network energy performance and the ability to exploit spectrum in very high frequency bands. Key technology components to reach these targets include flexible numerology, latency-optimized frame structure, massive MIMO, interworking between high and low frequency bands, and ultra-lean transmissions. Preliminary evaluations indicate that, with these technology components, NR can reach the 5G targets.

Introduction

The Third Generation Partnership Project (3GPP) is currently in the process of specifying a new fifth generation (5G) radio interface referred to as New Radio (NR) [1]. Mobile broadband (MBB) will continue to be important and drive the need for higher system capacity, better coverage, and higher data rates. However, the aim of 5G is much wider than that. One example is massive machine-type communication (mMTC), sometimes also referred to as the Internet of Things (IoT), where key challenges are to enable very low device cost and energy consumption, provide extreme coverage, and handle very large numbers of devices. Another example is ultra-reliable low-latency communication (URLLC), providing data delivery with unprecedented reliability in combination with very low latency, for example, targeting critical industry applications. Furthermore, during the lifetime of NR it is likely that new, not yet foreseen use cases will emerge. *Forward compatibility*, enabling smooth introduction of future optimizations, is therefore an important design principle. Network energy performance exceeding that of current systems is another key principle.

This article contains an overview of the emerging NR specifications, reflecting the situation as of November 2017 and describing what technology components are used to reach the above targets and enable the 5G use cases. An assessment of these technology components in terms of an evaluation against the IMT-2020 requirements defined by the International Telecommunication Union (ITU) is also included [1].

Standardization Phasing and Time Plan

Figure 1 outlines the 3GPP time schedule for NR specification and its relation to the IMT-2020 activities in ITU. To meet commercial requirements for early 5G deployments in 2018, the first NR specification will be available by the end of 2017, that is, even before the closure of 3GPP Release 15. The first specification will be limited to non-standalone NR operation, implying that NR deployments will rely on LTE for initial access and mobility. Standalone NR operation will be part of the final 3GPP Release 15 specification (mid-2018). The Release 15 specifications will focus on supporting MBB and URLLC, while the mMTC use case can be handled by, for example, the narrowband IoT (NB-IoT) technology developed by 3GPP. NR support for extended mMTC, as well as special technology features such as direct device-to-device connectivity, in 3GPP referred to as sidelink transmission, will be addressed in later releases. Full IMT-2020 [2] compliance will be part of 3GPP Release 16, to be finalized in 2019.

NR: Some Key Features

Higher-Frequency Operation and Spectrum Flexibility

One key feature of NR is a substantial expansion in terms of the range of spectrum in which the radio access technology can be deployed. Unlike LTE, where support for licensed spectrum at 3.5 GHz and unlicensed spectrum at 5 GHz is just being introduced, 3GPP has decided that NR will already from the start support operation from below 1 GHz up to 52.6 GHz[1] as well as operation in both licensed and unlicensed spectrum.

Operation at millimeter-wave (mmWave) frequencies offers the possibility for a very large amount of spectrum and very wide transmission bandwidths, enabling very high traffic capacity and very high data rates. However, higher frequencies are also associated with higher radio channel attenuation, limiting the network coverage. Although this can partly be compensated for by means of advanced multi-antenna transmission/reception, enabled by the smaller size of each antenna element, a substantial coverage disadvantage remains, especially in non-line-of-sight and outdoor-to-indoor propagation conditions. Thus, operation in lower frequency bands will remain a critical component for wireless communication in the 5G era. Specifically, joint operation in lower (e.g., below 3 GHz) *and* higher (e.g., mmWave) spectrum can provide substantial benefits. A higher-frequency layer with access to a large amount of spectrum will be able to provide service to a large fraction of users despite the more limited coverage. This will reduce the load on the more bandwidth-constrained lower-frequency spectrum, allowing the use of this to focus on the worst case users.

[1] The upper limit of 52.6 GHz is due to some very specific spectrum situations.

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The authors are with Ericsson Research.

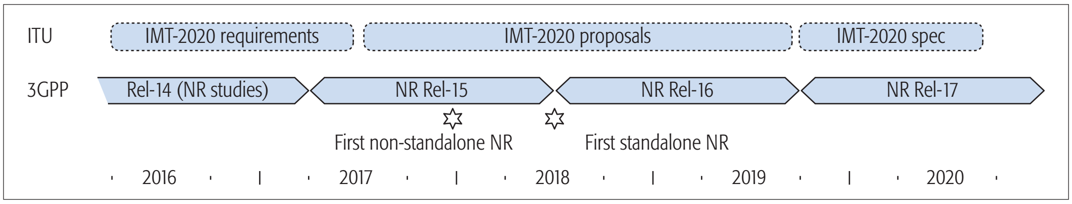

Figure 1. 5G timeline in 3GPP and ITU.

> Not all NR devices need to support the full carrier bandwidth, which has implications on the design on, for example, control channels as discussed later. Furthermore, NR allows for device-side receiver-bandwidth adaptation as a means to reduce the device energy consumption.

Ultra-Lean Design

An issue with current mobile communication technologies is the amount of transmissions carried by network nodes regardless of the amount of user traffic. Such signals, sometimes referred to as "always-on" signals, include, for example, signals for base station detection, broadcast of system information, and always-on reference signals for channel estimation. Under the typical traffic conditions of today, such transmissions constitute only a minor part of the overall network transmissions and thus have relatively small impact on network performance. However, in the future very dense networks deployed for very high peak rate, the average traffic load per network node can be expected to be relatively low, making always-on transmissions a more substantial part of the overall network transmissions.

The always-on transmissions have two negative impacts:

- They impose an upper limit on the achievable network energy performance.
- They cause interference to other cells, thereby reducing the achievable data rates.

The *ultra-lean design* principle aims at minimizing the always-on transmissions, thereby enabling higher network energy performance and higher achievable data rates.

Forward Compatibility

1 An important aim in the development of the NR specification has been to ensure a high degree of *forward compatibility* in the radio interface design. In this context, forward compatibility implies a radio interface design that allows for substantial future evolution in terms of introducing new technology and enabling new services with as yet unknown requirements and characteristics, while still supporting legacy devices on the same carrier.

Forward compatibility is inherently difficult to guarantee. However, based on experience from the evolution of previous generations, 3GPP agreed on some basic design principles related to NR forward compatibility as quoted from [3]:

- *Maximizing the amount of time and frequency resources that can be flexibly utilized or that can be left blanked without causing backward compatibility issues in the future*
- *Minimizing transmission of always-on signals*
- *Confining signals and channels for physical layer functionalities within a configurable/allocable time/frequency resource*

According to the third bullet, one should, as much as possible, avoid having transmissions on time/frequency resources fixed by the specification. In this way we retain flexibility for the future, allowing for later introduction of new types of transmissions with limited constraints from legacy signals and channels.

Note that these design principles partly coincide with the aim of ultra-lean design as described above. There is also a possibility in NR to configure reserved resources, that is, time-frequency resources that, when configured, are not used for transmission and are thus available for future radio interface extensions.

NR: Technology Overview

Transmission Scheme and Frame Structure

Similar to LTE [4], NR is based on orthogonal frequency-division multiplex (OFDM) transmission with the possibility of discrete Fourier transform (DFT) precoding for higher power amplifier efficiency in the uplink direction. However, to support a wide range of deployment scenarios, from large cells with sub-1 GHz carrier frequency up to mmWave deployments with very wide spectrum allocations, NR supports a flexible numerology with subcarrier spacings ranging from 15 kHz up to 240 kHz with a proportional change in cyclic prefix duration. A small subcarrier spacing has the benefit of providing a relatively long cyclic prefix in absolute time at a reasonable overhead, while higher subcarrier spacings are needed to handle, for example, the increased phase noise at higher carrier frequencies. Although the NR physical layer specification is band-agnostic, not all supported numerologies are relevant for all frequency bands. For each frequency band, radio requirements are therefore defined for a subset of the supported numerologies, as summarized in Table 1. Around 3300 subcarries are used, although the maximum total bandwidth is limited to 400 MHz, resulting in the maximum carrier bandwidths indicated in the table. If even larger bandwidths are to be supported, carrier aggregation can be used. Currently, there is no NR spectrum identified between 6 GHz and 24 GHz for NR, but requirements can easily be added at a later stage if such spectrum becomes available.

Not all NR devices need to support the full carrier bandwidth, which has implications on the design of, for example, control channels, as discussed later. Furthermore, NR allows for device-side *receiver-bandwidth adaptation* as a means to reduce the device energy consumption. Hence, NR defines so-called *bandwidth parts* that indicate the bandwidth over which a device is currently assumed to receive transmissions of a certain numerology. If a device is capable of simultaneous reception of multiple bandwidth parts, it is in principle possible to, on a single carrier, mix transmissions of different numerologies for a single device, although Release 15 only supports a single active bandwidth part at a time.

Frequency band	Subcarrier spacing	Maximum bandwidth
0.45 GHz–6 GHz	15/30/60 kHz	50/100/200 MHz
24 GHz–52.6 GHz	60/120 kHz	200/400 MHz

Table 1. Subcarrier spacing for different frequency ranges.

The NR frame structure is illustrated in Fig. 2. A 10 ms radio frame is divided into ten 1 ms subframes. A subframe is in turn divided into slots consisting of 14 OFDM symbols each, that is, the duration of a slot in milliseconds depends on the numerology. Thus, for the 15 kHz subcarrier spacing, an NR slot has the same structure as an LTE subframe, which is beneficial from a coexistence perspective. Since a slot is defined as a fixed number of OFDM symbols, a higher subcarrier spacing leads to a shorter slot duration. In principle, this could be used to support lower-latency transmission, but as the cyclic prefix also shrinks when increasing the subcarrier spacing, it is not a feasible approach in all deployments. Therefore, NR supports a more efficient approach to low latency by allowing for transmission over a fraction of a slot, sometimes referred to as "mini-slot" transmission. Such transmissions can also preempt an already ongoing slot-based transmission to another device, allowing for immediate transmission of data requiring very low latency.

Having the flexibility of starting a data transmission not only at the slot boundaries is also useful when operating in unlicensed spectrum. In unlicensed spectrum the transmitter is typically required to ensure that the radio channel is not occupied by other transmissions prior to starting a transmission, a procedure commonly known as listen-before-talk. Clearly, once the channel is found to be available, it is beneficial to start the transmission immediately, rather than wait until the start of the slot in order to avoid some other transmitter initiating a transmission on the channel.

Operation in the mmWave domain is another example of the usefulness of mini-slot transmissions as the available bandwidth in such deployments often is very large, and even a few OFDM symbols can be sufficient to carry the available payload. This is of particular use in conjunction with *analog beamforming*, discussed further below, where transmissions to multiple devices in different beams cannot be multiplexed in the frequency domain but only in the time domain.

Unlike LTE, NR does not include cell-specific reference signals but solely relies on user-specific demodulation reference signals for channel estimation. Not only does this enable efficient beamforming and multi-antenna operation, as discussed below; it is also in line with the ultra-lean design principle described above. Reference signals are not transmitted unless there is data to transmit, thereby improving network energy performance and reducing interference.

Support for low latency is an important part of NR that impacts many of the design details. One example is "front-loaded" transmissions (bottom, Fig. 2). By locating the reference signals and downlink control signaling carrying scheduling information at the beginning of the transmission and not using time-domain interleaving across OFDM symbols, a device can start processing the received data immediately without prior buffering, thereby minimizing the decoding delay.

Duplex Schemes

The duplex scheme to use is typically given by the spectrum allocation at hand. For lower frequency bands, allocations are often paired, implying frequency-division duplex (FDD). At higher frequency bands, unpaired spectrum allocations are increasingly common, calling for time-division duplex (TDD). NR will, similar to LTE, support both duplexing methods. However, unlike LTE where the TDD uplink-downlink allocation does not change over time, NR supports *dynamic TDD* as a key technology component. In dynamic TDD, (parts of) a slot can be dynamically allocated to either uplink or downlink as part of the scheduler decision. This enables following rapid traffic variations, which are particularly pronounced in dense deployments with a relatively small number of users per base station. The device follows any scheduling decisions, and it is up to the network scheduler to, if necessary, coordinate the scheduling decisions between neighboring sites to avoid unwanted interference situations. There is also a possibility to semi-statically configure the transmission direction of some of the slots, a feature that can allow for reduced device energy consumption as it is not necessary to monitor for downlink control channels in slots that are a priori known to be reserved for uplink usage.

Channel Coding

Channel coding for NR data transmission is based on low-density parity check (LDPC) codes [5]. LDPC codes are attractive from an implementation perspective, especially at multi-gigabits-per-second data rates. Hybrid automatic repeat request (ARQ) retransmission using incremental redundancy is used, similar to LTE, where the network can retransmit erroneously received data and the device combines the soft information from multiple transmission attempts.

For the physical layer control channels, for which the information blocks are small compared to data transmission and hybrid ARQ is not used, polar codes [6] have been selected. For the smallest control payloads, Reed-Muller codes are used.

Scheduling, Data Transmission, and Control Channels

The basic way of controlling data transmission in NR is scheduling in a similar way as in LTE. Each device monitors a number of physical downlink control channels (PDCCHs), typically once per slot although it is possible to configure more frequent monitoring to support traffic requiring very low latency. Upon detection of a valid PDCCH, the device follows the scheduling decision and receives (or transmits) one unit of data, known as a transport block in NR.

The PDCCHs are transmitted in one or more control resource sets (CORESETs) each of length one to three OFDM symbol(s). Unlike LTE, where control channels span the full carrier bandwidth, the bandwidth of a CORESET can be configured. This is needed in order to handle devices with different bandwidth capabilities and also in line with the principles for forward compatibility discussed above.

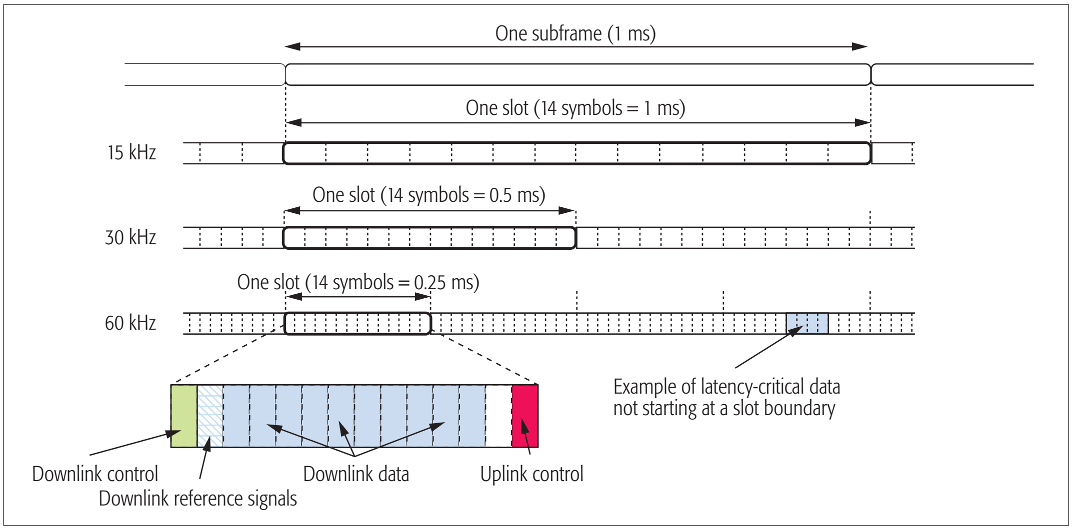

FIGURE 2. Frame structure (TDD assumed in this example).

Support for a massive number of steerable antenna elements for both transmission and reception is a key feature of NR. At higher frequency bands, the large number of antennas elements are primarily used for beamforming to achieve coverage, while at lower frequency bands they enable full-dimensional MIMO and interference avoidance by spatial filtering.

Upon reception of downlink data, the device responds with a hybrid ARQ acknowledgment indicating whether the data transmission was successful or not. Given the very high data rates supported by NR, the transport block size can become very large. Retransmitting the whole transport block could in this case become inefficient. NR therefore supports retransmissions at a finer granularity, known as code-block group (CBG). This can also be useful when handling preemption mentioned earlier. An urgent transmission to a second device may use only one or a few OFDM symbols and therefore cause high interference to the first device in some OFDM symbols only. In this case it may be sufficient to retransmit the interfered CBGs only and not the whole data block. Handling of preempted transmission can be further assisted by the possibility of indicating to the first device the impacted time-frequency resources such that it can take this information into account in the reception process.

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Hybrid ARQ acknowledgments, as well as other uplink control information, such as channel-state feedback for multi-antenna operation and scheduling request for uplink data awaiting transmission, are transmitted using the physical uplink control channel (PUCCH). There are several different PUCCH formats, depending on the amount of information and the duration of the PUCCH transmission. A *short PUCCH* is transmitted in the last one or two symbols of a slot and can support very fast feedback of hybrid ARQ acknowledgments in order to realize so-called self-contained slots where the delay from the end of the data transmission to the reception of the acknowledgment from the device is on the order of an OFDM symbol, corresponding to a few tens of microseconds depending on the numerology used. This can be compared to almost 3 ms in LTE and illustrates the focus on low latency in NR. For situations when the duration of the short PUCCH is too short to provide sufficient coverage, there are also possibilities for longer PUCCH durations.

Although dynamic scheduling is the basic operation of LTE, semi-persistent scheduling can be configured. In this case, the device is configured in advance with resources that can be used for uplink data transmission (or downlink data reception). Once a device has data available, it can immediately commence uplink transmission without going through the scheduling request-grant cycle, enabling lower latency.

BEAMFORMING AND MULTI-ANTENNA TRANSMISSION

Support for a massive number (e.g., ≥ 64) of steerable antenna elements for both transmission and reception is a key feature of NR. At higher frequency bands, the large number of antenna elements are primarily used for beamforming to achieve coverage, while at lower frequency bands they enable full-dimensional multiple-input multiple-output (MIMO) and interference avoidance by spatial filtering.

NR channels and signals, including those used for control and synchronization, have all been designed for optional beamforming. Channel state information (CSI) for operation of massive multi-antenna schemes can be obtained by feedback of CSI reports based on transmission of CSI reference signals in the downlink, either per antenna element or per beam, as well as using uplink measurements exploiting channel reciprocity.

To give flexibility in implementation choice, NR is deliberately introducing functionality to support analog beamforming in addition to digital precoding/beamforming. At high frequencies, analog beamforming, where the beam is shaped after digital-to-analog conversion, may be necessary from an implementation perspective, at least initially. Analog beamforming results in the constraint that a receive or transmit beam can only be formed in one direction at a given time instant and requires beam-sweeping where the same signal is repeated in multiple OFDM symbols but in different transmit beams. With beam-sweeping possibility, it is ensured that any signal can be transmitted with a high gain, narrow beamformed transmission to reach the entire intended coverage area.

Beam management procedures and signaling are specified, such as indication to the device to assist selection of a receive beam (in the case of analog receive beamforming) to be used for data and control reception, respectively. For a large

For NR, extended support for such multi-user spatial multiplexing is introduced, by either using high-resolution CSI feedback with a linear combination of DFT vectors, or uplink sounding reference signal improvements targeting the utilization of channel reciprocity.

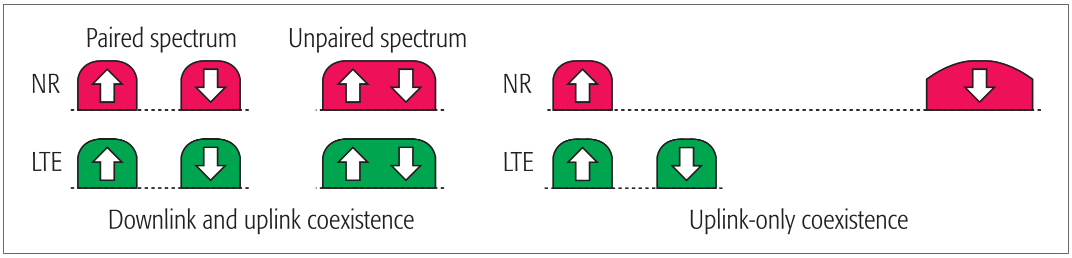

FIGURE 3. NR-LTE coexistence.

number of antennas, beams are narrow and beam tracking can fail; therefore, beam recovery procedures have also been defined where a device can trigger a beam recovery procedure. Moreover, a cell may have multiple transmission points, each with beams, and the beam management procedures allow for device-transparent mobility for seamless handover between the beams of different points. Additionally, uplink-centric and reciprocity-based beam management is possible by utilizing uplink signals.

With the use of a massive number of antenna elements for lower frequency bands, the possibility to separate users spatially increases in both uplink and downlink but requires that the transmitter has channel knowledge. For NR, extended support for such multi-user spatial multiplexing is introduced, either by using high-resolution CSI feedback with a linear combination of DFT vectors, or uplink sounding reference signal improvements targeting the utilization of channel reciprocity.

In addition, support for distributed MIMO is introduced, where the device can receive multiple PDCCH and multiple physical data shared channels (PDSCHs) per slot to enable simultaneous data transmission from multiple transmission points to the same user.

Twelve orthogonal demodulation reference signals are specified for multi-user MIMO transmission, while an NR device can maximally receive eight MIMO layers. Moreover, additional configuration of a phase tracking reference signal is introduced in NR since the increased phase noise power at high carrier frequency bands otherwise will degrade demodulation performance for larger modulation constellations, such as 64-quadrature amplitude modulation (QAM).

INITIAL ACCESS

The basic structure of NR initial access is similar to the corresponding functionality of LTE [4]:

- There is a pair of downlink signals, the primary synchronization signal (PSS) and secondary synchronization signal (SSS), that is used by user equipment (UE) to find, synchronize to, and identify a network
- There is a downlink physical broadcast channel (PBCH) transmitted together with the PSS/SSS. The PBCH carries a minimum amount of system information including indication of where the remaining broadcast system information is transmitted. In the context of NR, the PSS, SSS, and PBCH are jointly referred to as a synchronization signal (SS) block.
- There is a four-stage random access procedure, commencing with the uplink transmission of a *random access preamble*

However, there are some important differences between LTE and NR in terms of initial access.

In LTE, the PSS, SSS, and PBCH are located at the center of the carrier and are transmitted once every 5 ms. Thus, by dwelling on each possible carrier frequency for at least 5 ms, a device is guaranteed to receive at least one PSS/SSS/PBCH transmission if a carrier exists at the specific frequency. Without any a priori knowledge, a device must search all possible carrier frequencies over a carrier raster of 100 kHz.

To enable higher NR network energy performance, the SS block is, by default, transmitted once every 20 ms. Due to the longer period between consecutive SS blocks, compared to the corresponding signals/channels in LTE, a device searching for NR carriers must dwell on each possible frequency for a longer time. To reduce the overall search time while keeping the device complexity comparable to LTE, NR supports a *sparse frequency raster* for the SS block. This implies that the possible frequency-domain positions of the SS block could be significantly sparser compared to the possible positions of an NR carrier (the *carrier raster*). As a consequence, the SS block will typically not be located at the center of the NR carrier.

The sparse SS block raster enables significantly reduced time for initial cell search; at the same time, the network energy performance can be significantly improved due to the longer SS block period.

Network-side beam sweeping is supported for both downlink SS block transmission and uplink random access reception as a means to improve coverage, especially in the case of operation at higher frequencies.

INTERWORKING AND LTE COEXISTENCE

As it is difficult to provide full coverage at higher frequencies, interworking with systems operating at lower frequencies is important. In particular, a coverage imbalance between uplink and downlink is a common scenario, especially if they are in different frequency bands:

- Due to, in general, higher transmit power for the base station compared to the mobile device, the downlink achievable data rates are more often bandwidth limited, making it more relevant to operate the downlink in higher spectrum where wider bandwidth may be available.
- In contrast, the uplink is more often power limited, reducing the need for wider bandwidth. Instead, higher data rates may be achieved on lower-frequency spectrum, despite less available bandwidth, due to less radio channel attenuation.

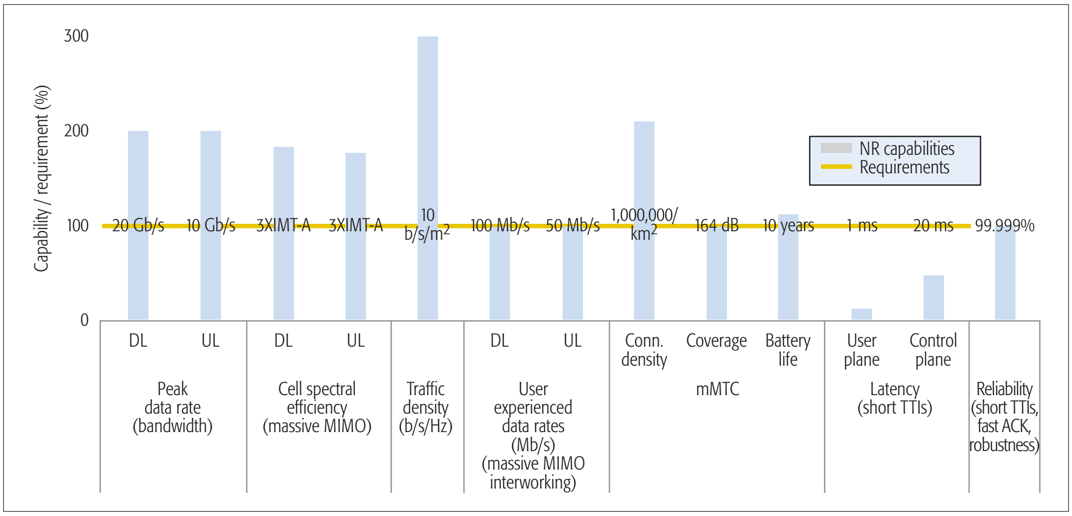

Figure 4. IMT-2020 and 3GPP requirements, enabling technologies, and achieved performance.

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Through interworking, a high-frequency NR system can complement a low-frequency system. The lower-frequency system can be either NR or LTE, and NR supports interworking with either of these. The interworking can be realized at different levels, including intra-NR carrier aggregation, dual connectivity with a common packet data convergence protocol (PDCP) layer, and handover.

However, the lower-frequency bands are often already occupied by current technologies, primarily LTE. Furthermore, additional low-frequency spectrum is planned to be deployed with LTE in the relatively near future. LTE/NR *spectrum coexistence*, that is, the possibility for an operator to deploy NR in the same spectrum as an already existing LTE deployment, has therefore been identified as a way to enable early NR deployment in lower frequency spectrum without reducing the amount of spectrum available to LTE.

Two coexistence scenarios have been identified in 3GPP:

- In the first scenario, illustrated on the left of Fig. 3, there is LTE/NR coexistence in both downlink and uplink. Note that this is relevant for both paired and unpaired spectrum.
- In the second scenario, illustrated on the right of Fig. 3, there is coexistence only in the uplink transmission direction, typically within the uplink part of lower-frequency paired spectrum, with NR downlink transmission taking place in spectrum dedicated to NR, typically at higher frequencies. This scenario attempts to address the uplink-downlink imbalance discussed above.

The possibility of an LTE-compatible NR numerology based on 15 kHz subcarrier spacing, enabling identical time/frequency resource grids for NR and LTE, is one of the fundamental tools for such coexistence. The flexible NR scheduling with a scheduling granularity as small as one symbol can then be used to avoid scheduled NR transmissions colliding with key LTE signals such as cell-specific reference signals, CSI-RS, and the signals/channels used for LTE initial access. The possibility to configure reserved resources introduced for forward compatibility, discussed earlier, can also be used to further enhance NR-LTE coexistence.

NR: Performance

To improve existing use cases and enable new ones, a set of technical requirements are defined for NR; see [1] for a subset of those along with enabling technologies and expected performance levels.

For MBB, NR will support peak rates twice the ITU requirements of 20 Gb/s downlink and 10 Gb/s uplink, enabled foremost by wide bandwidth, and user-plane latency well below 1 ms (Fig. 4). User experienced data rates, to be reached with 95 percent probability in loaded conditions, of 100 Mb/s downlink and 50 Mb/s uplink will also be achieved, together with spectral efficiencies at least three times higher than required in IMT-Advanced. Massive MIMO and interworking between low and high bands are the main enablers in this case. For the spectral efficiency evaluations in Fig. 4, coherent massive MIMO utilizing 64–256 base station antenna elements, depending on frequency band, and supporting multi-user MIMO is used.

Targeting mMTC usage, using NB-IoT technology deployed with an inter-site distance of 1732 m, connection densities far exceeding the requirement of 1,000,000 devices per square kilometer are achieved. 20 dB coverage improvements (resulting in a coupling loss of 164 dB) and battery lives exceeding 10 years are also supported. URLLC is supported with success probabilities exceeding 99.999 percent within a delay not exceeding 1 ms at the cell edge, characterized by about –4 dB signal-to-interference-plus-noise ratio (SINR). This is supported by low code rates, antenna diversity, and fast and adaptive transmissions.

Not included in Fig. 4, ultra-lean transmission is an enabler for improved network energy performance, where the 20 ms periodicity of the SS block makes it possible to put more components to sleep for a longer time, enabling close to a factor of 10 improvement in energy performance over current systems.

To summarize, using the NR technology components the requirements can be reached, and the targeted use cases thereby are indeed enabled.

In addition to the ITU and 3GPP requirements, a fundamental prerequisite from many operators

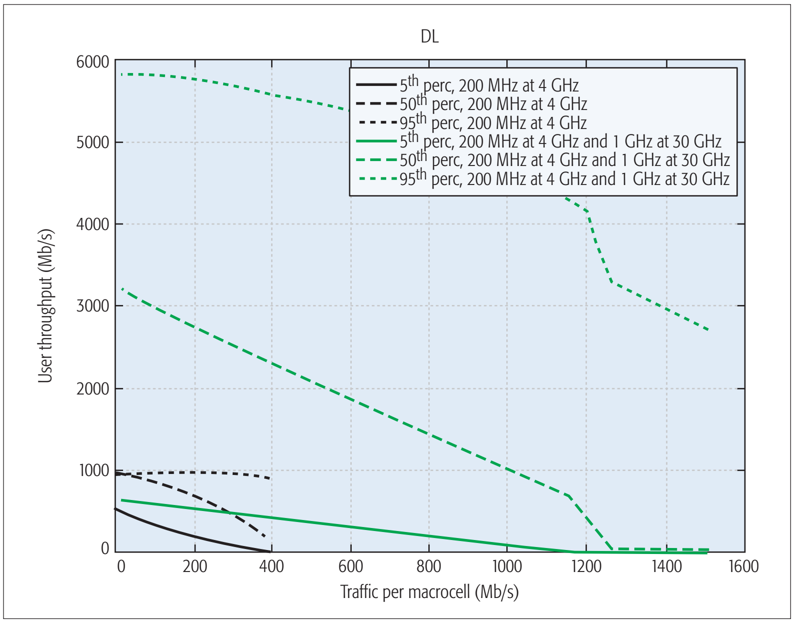

Figure 5. Downlink user throughput percentiles (5th, 50th, and 95th) as a function of served traffic per macrocell.

is that NR should be deployable and valuable using their existing site and frequency assets. To this end, interworking with lower bands is very important. To demonstrate this, the usability of the 30 GHz band in the macro layer in the ITU Dense Urban scenario is evaluated by means of system-level simulations of a preliminary NR system with basic functionality (Fig. 5). Deployment and propagation models and parameters are aligned with [1, 2], and a file transfer traffic model is used.

Figure 5 shows downlink user throughput as a function of traffic load for two different system configurations: one using only the 4 GHz band (200 MHz bandwidth) and one using both the 4 GHz band and the 30 GHz band (1 GHz bandwidth). It is seen that the additional use of the 30 GHz band results in significantly improved user throughput and served traffic due to the offloading to the 30 GHz carrier, which has much higher bandwidth. Due to the higher attenuation at 30 GHz, the user throughput at the 5th percentile and at low load is not much improved. For higher loads there is a large gain even for cell edge users due to the reduced interference and queuing in the 4 GHz carrier by offloading. At higher traffic loads, there is user throughput gain at all percentiles. In terms of served traffic for a certain user throughput requirement, there is also a large gain. Similar results are achieved for combinations of lower frequency bands in systems with larger inter-site distances. Combination with a lower frequency enables usage of a high frequency band despite its challenging propagation.

Conclusion

NR is the new 5G radio interface, capable of addressing a wide range of use cases and reaching very aggressive performance targets. Some of the key technology components to reach these targets include flexible numerology, a latency-optimized frame structure, massive MIMO, interworking between high and low frequency bands, and ultra-lean transmissions. The first version of NR will be ready by the end of 2017 and provide a platform for future evolution many years to come.

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Biographies

Stefan Parkvall [F] (stefan.parkvall@ericsson.com) is currently a principal researcher at Ericsson Research working with research on 5G and future radio access. He is one of the key persons in the development of HSPA, LTE, and NR radio access and has been deeply involved in 3GPP standardization for many years. He served as an IEEE Distinguished Lecturer 2011–2012, and is co-author of the books *3G Evolution — HSPA and LTE for Mobile Broadband*, *4G — LTE/LTE-Advanced for Mobile Broadband*, and *4G — LTE Advanced Pro and the Road to 5G*. He has more than 1000 patents in the area of mobile communication. In 2005, he received the Ericsson "Inventor of the Year" award, in 2009 the Swedish government's Major Technical Award for his contributions to the success of HSPA, and in 2014 he and colleagues at Ericsson were one of three finalists for the European Inventor Award, the most prestigious inventor award in Europe, for their contributions to LTE. He received his Ph.D. degree in electrical engineering from the Royal Institute of Technology in 1996. His previous positions include assistant professor in communication theory at the Royal Institute of Technology, Stockholm, Sweden, and a visiting researcher at the University of California, San Diego.

Erik Dahlman is currently a senior expert in Radio Access Technologies within Ericsson Research. He was deeply involved in the development and standardization of 3G radio access technologies (WCDMA and HSPA), first in Japan and later within the global 3GPP standardization body. Later on he was involved in the standardization/development of 3GPP LTE and its continued evolution. His is currently involved in the standardization and development of the next generation 5G wireless access technologies. He is co-author of the books *3G Evolution — HSPA and LTE for Mobile Broadband*, *4G — LTE and LTE-Advanced for Mobile Broadband*, and, most recently, *4G — LTE-Advanced Pro and The Road to5G*. He is a frequent invited speaker at different international conferences and holds more than 100 patents within the area of mobile communication. In 2009, he received the Major Technical Award, an award handed out by the Swedish Government, for his contributions to the technical and commercial success of the 3G HSPA radio access technology. In 2014 he was nominated for the European Inventor Award, the most prestigious inventor award in Europe, for contributions to the development of 4G LTE.

Anders Furuskär received an M.Sc. degree in electrical engineering and a Ph.D. degree in radio communications systems from the Royal Institute of Technology in 1996 and 2003, respectively. He joined Ericsson Research in 1997 and currently holds the position of senior expert, focusing on radio resource management and performance evaluation of wireless networks.

Mattias Frenne joined Ericsson in 2011 and is a senior specialist in the area of multi-antenna signal processing. He has contributed to both physical layer concept development and as a standardization delegate of LTE and NR in 3GPP RAN WG1. He holds M.Sc. (1996) and Ph.D. (2002) degrees in engineering physics and signal processing, respectively, both from Uppsala University, Sweden. He was named Ericsson Inventor of the Year in 2016.