1

Introduction and Background

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1.1 Why 5G?

It is perhaps a reasonable question to ask why we need 5G? Was in fact 4G/LTE and its evolution sufficient? Looking at LTE we note that indeed, we identify a good set of advanced technical components (speaking from the perspective of physical layer): it has multiple antennas scaling to the possibility to use massive MIMO (Multiple Input Multiple Output), it supports emerging connectivity techniques such as device-to-device, NB-IoT, Ultra Reliable and Low Latency Communications (URLLC). So why 5G? Every decade seems to bring a new wave of technology, this was the case with the arrival of 3G and 4G. From this basic perspective, the arrival of 5G strengthens this "rule." Is there a need for 5G, especially given the fact that LTE and LTE-pro are capable of delivering high data rates and flexible technology? Yes, there is a need for 5G and there are a couple of reasons which we will elaborate next.

Like any evolving system, LTE has reached the limit of being a complicated design, its limitations coming from the fact that the basic design conceived a decade ago cannot be updated further in a simple way and cannot be kept easily compatible with the earlier equipment. The evolution of 3GPP generations has maintained the rule that all new devices are able to function in the older networks and vice versa without loss of functionality. As some of the components introduced at the very beginning of 4G need complicated solutions in order to be optimized, new functionality must be introduced so that compatibility with the old functionality is maintained. To give a simple example, the very first LTE release was designed based on Common Reference Signals (CRSs), up to four ports, which are transmitted all the time, hence they are always ON. However, the system cannot turn these reference signals OFF, nor can scale them when the number of antennas is increasing at the transmitter without causing complications to existing device base. While CRS were a good design at its time, it was also unscalable in the future, by scalability meaning, for example, increasing the number of ports as the number of transmit antennas increases. Perhaps one of the most important lessons learned from LTE is indeed the need for a more flexible and scalable system toward the future. This is an intrinsic characteristic of 5G NR design and we are covering perhaps the most important new development over LTE, the multi-antenna perspective, in this book.

5G New Radio: A Beam-based Air Interface, First Edition. Edited by Mihai Enescu.

Another reason for 5G is the need for harvesting the spectrum where cellular technology has not been used so far. Spectrum is a costly resource, not easy to handle in a global environment, especially keeping in mind the cost of both devices and network equipment. 4G/LTE has been deployed in the low bands and with these occupied, there is an obvious need and choice to evolve to the areas of unoccupied spectrum to obtain more capacity for the system in general. Most of the first deployments rely on mid band of 3.5/4.5 GHz as well as 28/39 GHz, bands that are mostly unoccupied by LTE in the lower end, and lacking ability for LTE to be even deployed on in on the higher end. While moving to higher frequency bands not earlier used for cellular radio transmissions is not an easy step, it comes with the good news that the antenna form factor gets smaller as the carrier frequency gets higher. However, a lot of other challenges are arising from the fact that the pathloss on higher frequencies is also higher, and the power amplifier technologies need to evolve to support sufficient transmit powers with reasonable energy efficiency in a consumer device price point. As a first step, the 5G NR is designed to operate on bands starting from under 1 GHz and reaching up to 52 GHz, with more design focus to come in the area of 52 GHz and beyond.

The need for this book came from the fact that it seems necessary to link the dots of the existing 5G specifications into a cursive description of what the system is about and why it has been created the way it is. This book has been written by standardization experts who have been and currently are participating actively in 3GPP discussions. Most of them have also been involved in designing the 4G system with the area of expertise reaching back to 2G and 3G. We hope that the description herein will help the reader into getting a better understanding of how the 5G physical layer and related higher layer components are functioning and especially why they were designed to function that way.

While the existing 3GPP standards describe what has been agreed in the meetings, in this book we want to take this one step further and also present the context of some of the discussions and various alternatives which have been discussed but, in the end, not adopted as a standardized solutions.

1.2 Requirements and Targets

The 5G specification work was preceded by a study whose objective [1] was to identify and develop technology components needed for new radio (NR) systems being able to use any spectrum band ranging at least up to 100 GHz. The goal was to achieve a single technical framework addressing all usage scenarios, requirements, and deployment scenarios defined in TR38.913 [2]. This TR was defined to ensure that the ITU-R IMT-2020 requirements [3] will be covered, and additional industry needs are also taken into account in the technical work. Naturally the requirements were not developed in a vacuum but based on the practical understanding of what should also be achievable in real life without the need to violate the laws of physics. The new radio access technology (RAT) was to be designed for inherent forward compatibility to allow specification in multiple phases and cater for the needs of the future that today we can't imagine. This design requirement was also learning from LTE, which had a somewhat rigid setup of always-own full-band CRS and fairly fixed carrier bandwidth structure even if the original LTE design has regardless of these things proven itself to be very capable of integrating new features over a number of subsequent

3GPP releases. The New Radio study item contained technical features needed to meet these objectives set in the said TR38.913 [2]. In addition to very demanding performance requirements the additional functional requirements include:

- Tight interworking between the new RAT and LTE
- Interworking with non-3GPP systems
- Operation in licensed bands (paired and unpaired), and licensed assisted operations in unlicensed bands.
- Stand-alone operation in unlicensed bands.

One of the focus areas for the initial work related to defining a fundamental physical layer signal structure for new RAT, the key topics in this area including waveform, frame structure(s), and channel coding scheme(s).

1.2.1 System Requirements

In order to understand how wireless technologies are being created and especially labeled, it is necessary to discuss briefly about IMT-2020. There is indeed a basic question: who is certifying that a particular technology can be called 5G and based on what criteria is this done?

The International Telecommunications Union (ITU), based in Geneva, Switzerland, is a United Nations agency responsible for issues related to the communications technology. The areas of ITU cover Radio communications (ITU-R), Standardization (ITU-T), Development (ITU-D). In order to have a unified certification system on a global scale, technologies must be certified by ITU-R. This is based on ITU-R-crafted requirements, for a technology being labeled as 5G, this needs to pass these ITU requirements. The first NR release is already done, however, in order for this to be called a 5G technology, this design must pass the ITU-R requirements, this evaluation being done during the IMT-2020 discussions. According to the IMT-2020 vision, a 5G technology needs to reach requirements presented in Figure 1.1 [4].

The area of 5G requirements is crafted around the three main development cases: Extreme Mobile Broadband (eMBB), URLLC, and Massive Machine Type Communications (mMTC). eMBB capabilities relate to the maximum achievable data rate in terms of peak data rate (20 Gbps) but also in terms of coverage (1 Gbps), a high speed environment where quality of service (QoS) needs to be met for 500 kmph, an energy efficient operation at least similar to 4G and the possibility for delivering services in dense areas where the total traffic across the coverage area is of 1000 Mbps m^{-2}. URLLC has its own requirements of a very tight latency (round trip time) of 1 ms while the eMBB target of mobility needs also to be met. Finally, mMTC targets a total number of devices per unit area of 10 000 devices per km^2.

This vision was worked further, and to some extent in parallel with the 3GPP requirement and evaluation environment definition, and a more thorough requirement document with a very detailed evaluation methodology document were later produced by ITU.R. [5, 6] (summarized in Table 1.1). In some cases, the requirement name alone is insufficient to understand what is required, as what matters is how the detailed definition and the test setup have been defined. E.g. the user experienced data rate refers to a cell edge user defined as a 5th

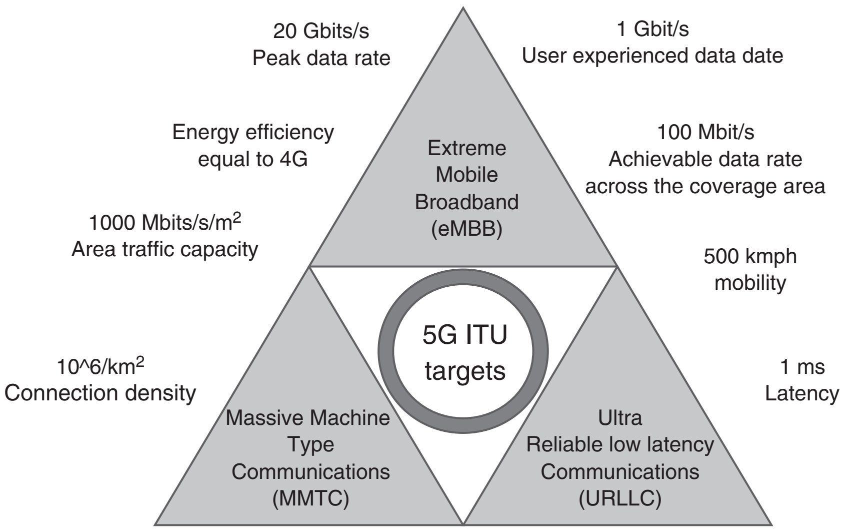

Figure 1.1 ITU-R vision for 5G [4].

percentile point in the cumulative distribution function in a setup where there are 10 users in each cell of the system all of them having data to be scheduled. This leads to 100% loading in all cells all the time generating both worst case own cell loading and worst possible other cell interference. The simulation scenarios for evaluation are defined in fine detail in [6].

The 3GPP RAN meeting #70 in December 2015 opened a study on scenarios and requirements for Next Generation Access Technologies [7]. The draft Technical Report of the System Information (SI) [2] released in March 2016 consisted of a large number of requirements that were used as a basis for the physical layer design work. The RAN#71 (in March 2016) also approved a new study on New Radio (NR) Access Technology that tasked the Radio Access Network (RAN) WGs "…*to develop an NR access technology to meet a broad range of use cases including enhanced mobile broadband, massive MTC, critical MTC, and additional requirements defined during the RAN requirements study*" [8].

The Requirements and Scenarios Technical Report [2] listed a large number of requirements to which the physical layer of the 5G New Radio is to provide solutions, which are summarized in the list below:

- A very *diverse set of deployments* ranging from Indoor Hotspot to Extreme Rural coverage
- A *wide range of spectrum bands* up to 100 GHz *and bandwidths* up to 1 GHz
- Wide range of *device speeds*, up to 500 kmph
- *Ultra-deep indoor coverage* with tentative target of 164 dB MCL
- *D2D/V2V links*
- Target *peak rate of 20 Gbps in downlink and 10 Gbps in uplink*
- Significantly *improved system capacity, user data rates and spectral efficiency* over LTE
- Target *C-plane latency* of 10 ms
- Target *U-plane latency* of 4 ms for mobile broadband, and 0.5 ms for *ultra low latency* communication
- Target *mobility*-incurred *connection interruption of 0 ms*

Table 1.1 ITU-R requirements for IMT-2020 [5].

Requirement name	Minimum requirement
Peak data rate	DL: 20 Gbps, UL: 10 Gbps
Peak spectral efficiency	DL: 30 bps Hz^{-1}, UL: 15 bps Hz^{-1}
User experienced data rate	DL: 100 Mbps, UL: 50 Mbps
5th percentile user spectral efficiency	Indoor hotspot – DL: 0.3 bps Hz^{-1}, UL 0.21 bps Hz^{-1} Dense urban – DL: 0.225 bps Hz^{-1}, UL 0.15 bps Hz^{-1} Rural – DL: 0.12 bps Hz^{-1}, UL 0.045 bps Hz^{-1}
Average spectral efficiency	Indoor hotspot – DL: 9 bps Hz^{-1}, UL 6.75 bps Hz^{-1} Dense urban – DL: 7.8 bps Hz^{-1}, UL 5.4 bps Hz^{-1} Rural – DL: 3.3 bps Hz^{-1}, UL 1.6 bps Hz^{-1}
Area traffic capacity	10 Mbps m^{-2}
User plane latency	4 ms for eMBB, 1 ms for URLLC
Control plane latency	20 ms requirement, 10 ms encouraged
Connection density	1 000 000 devices km^{-2}
Energy efficiency	Network energy efficiency is the capability of a RIT/SRIT to minimize the radio access network energy consumption in relation to the traffic capacity provided. Device energy efficiency is the capability of the RIT/SRIT to minimize the power consumed by the device modem in relation to the traffic characteristics.
Reliability	The minimum requirement for the reliability is 99.999% success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-URLLC test environment
Mobility link spectral efficiency	Indoor hotspot 10 kmph—1.5 bps Hz^{-1} Dense urban 30 kmph–1.12 bps Hz^{-1} Rural 120 kmph–0.8 bps Hz^{-1} Rural 500 kmph–0.45 bps Hz^{-1}
Mobility interruption time	0 ms
Bandwidth	At least 100 MHz and up to 1 GHz in higher frequency bands

- Target *reliability* of delivering a packet in 1 ms with 1-10^{-5} reliability
- Tentative target *User Equipment (UE) battery life of 15 years* for *massive MTC* type terminals
- Improved *UE energy efficiency* while providing much better MBB data rate
- Improved *network energy efficiency*
- Target connection *density of 1 million devices* km^{-2}
- Tight *interworking with LTE*
- Connectivity through *multiple transmission points*
- Operator-controlled *sidelink (device-to-device) operation*

Looking at the above list of diverse requirements and deployment environments envisioned for New Radio system, they cannot be met with a single monolithic physical layer design – but rather by a physical layer design that is able to adapt to different deployments and use cases, all these in a common operation framework.

At least the following implications to the physical layer design were derived from the requirement list presented in Section 2.1:

- Both frequency division duplex (FDD) and time division duplex (TDD) need to be supported to be able to deploy the New Radio on all bands from sub-1 GHz up to 100 GHz.
- The network topologies will depend on the operating carrier frequency, a possible split being roughly as listed in the following points.
- The ultra-deep indoor coverage operation of mMTC would be applicable for low band frequencies, e.g. below 1 GHz, while high band frequencies could potentially support a different category of mMTC applications such as household appliances, this latter category not having the same coverage requirements as the low band mMTC.
- There may not be a need to optimize FDD for high bands (e.g. above 3 GHz) due to the fact that most known band plans above 3 GHz are either TDD or unidirectional.
- A single numerology for all cases as in LTE is not sufficient to support very wide bandwidth and relatively small coverage cells closer to 100 GHz band range, and large coverage cells around traditional cellular bands and bandwidths.
- The same multicarrier OFDMA waveform suitable e.g. for eMBB use cases up to around 40 GHz may not be optimal for, e.g. narrow-band mMTC type links and eMBB links above 40 GHz. A single-carrier waveform should be considered for these cases.
- A single fixed slot duration is not sufficient for meeting both ultra-reliability requirements as well as extreme rural and deep indoor coverage.
- Operation on unlicensed frequencies calls for Listen Before Talk or similar interference management technique.
- Wireless relay may have special implications to control channel design, beam detection, reference signals, and interference management.
- D2D/V2V sets specific requirements to accommodate for the time misalignment and has special implications to control channel and reference signal design.
- Network energy efficiency requirement needs to be addressed with minimizing the network transmission in no-data TTIs (e.g. synchronization signals, CRS, Physical Broadcast Channel [PBCH]).
- Consider enabling UEs that do not support the full system BW in order natively to enable low-cost IoT devices.
- Develop advanced Massive MIMO framework that scales from low band digital beamforming/MIMO to high-band analogue/hybrid beamforming with very large number of antenna elements.

Some of the above implications can be summarized in Table 1.2 as follows:

Initially the need for supporting all features across the full frequency range was debated, partially because the design characteristics needed for the support of high order antenna arrays was not yet known. Once the base design started to form, the desire to be able to deploy all features on all frequency ranges was becoming more evident, and the solutions being designed were more and more obviously agnostic to frequency bands. The one exception to the norm was some specific design details supporting analogue component of the beamformers that is essentially just applicable for high frequency bands.

Table 1.2 Summary of 5G NR technology components.

	Below 2 GHz	2–6 GHz	3–40 GHz	20–100 GHz
Network topology	Wide area deployment	Urban area deployment	Small cell deployment	Small and ultra-dense small cells
Technologies	eMBB, mMTC, URLLC		eMBB (URLLC)	eMBB
Waveform	OFDMA based, consider contention based and/or non-orthogonal access		OFDMA based	ZT-DFT-s-OFDM/ Null CP-single carrier
Frame structure	Unified and flexible across deployments			
Multi antenna	Digital BF		Digital/analogue/ hybrid BF	Analogue/ hybrid BF
	Unified feedback framework, base station processing transparent to the UE, CSI feedback agnostic to base station processing			
Mobility	Decreasing with the increase of frequency band operation and with decreasing cell size			

1.2.2 5G Spectrum

Spectrum availability is the corner stone for 5G NR development and deployment. The large amount of use cases as described in the previous section, implies a more efficient utilization of the existing spectrum as well as the identification of new spectrum for cellular use. LTE and other legacy cellular radio deployments are operating in relatively low frequency bands, these bands fitting well for eMBB services and mMTC deployments. This is because the radio propagation characteristics in low bands allow for a good compromise between coverage for a given base station as well as capacity through being able to use the same frequency resource with a neighboring base station without requiring a very large distance between the two base stations [29]. The established volume market has also led to the availability of simple, low cost radio implementations for those frequency bands. 5G deployments are likely to benefit from the refarming of this spectrum range, hence in time, at least some of the bands today known as 2G, 3G, or LTE bands will be migrated to 5G use. However, higher frequency bands not used by cellular and not accessible to the earlier generations due to technology limitations also become a deployment possibility with NR – if such new bands can be identified for cellular use.

3GPP does not have control over frequency allocations or bands, and it does not specify a particular frequency band unless the band is available or becoming available for cellular use in some part of the world, but the 3GPP system design in itself is band agnostic up to a point – there are some limitations to how high or how low the 3GPP-defined technologies can practically go, as well as what bandwidths the different generations support. ITU-R, regional and national regulators are identifying a new spectrum, while 3GPP is defining these bands in order to create the necessary radio frequency (RF) requirements which are band specific. In Tables 1.3 and 1.4 we present the 3GPP defined bands as of summer 2019. There are several types of identified spectrum: paired bands used for FDD, unpaired bands used for TDD, unpaired bands used for SUL (Supplemental uplink) or SDL (Supplemental

Table 1.3 Spectrum bands for low-to-mid frequency (FR1).

Operating band	Total spectrum (MHz)	Uplink (MHz)	Downlink (MHz)	Duplex mode
n1	2 × 60	1920–1980	2110–2170	FDD
n2	2 × 60	1850–1910	1930–1990	FDD
n3	2 × 75	1710–1785	1805–1880	FDD
n5	2 × 25	824–849	869–894	FDD
n7	2 × 70	2500–2570	2620–2690	FDD
n8	2 × 35	880–915	925–960	FDD
n12	2 × 17	699–716	729–746	FDD
n20	2 × 30	832–862	791–821	FDD
n25	2 × 65	1850–1915	1930–1995	FDD
n28	2 × 45	703–748	758–803	FDD
n34	15	2010–2025	2010–2025	TDD
n38	50	2570–2620	2570–2620	TDD
n39	40	1880–1920	1880–1920	TDD
n40	100	2300–2400	2300–2400	TDD
n41	194	2496–2690	2496–2690	TDD
n50	85	1432–1517	1432–1517	TDD
n51	5	1427–1432	1427–1432	TDD
n66	70 + 90	1710–1780	2110–2200	FDD
n70	15 + 25	1695–1710	1995–2200	FDD
n71	2 × 35	663–698	617–652	FDD
n74	2 × 43	1427–1470	1475–1518	FDD
n75	1 × 85	—	1432–1517	SDL
n76	1 × 5	—	1427–1432	SDL
n77	900	3300–4200	3300–4200	TDD
n78	500	3300–3800	3300–3800	TDD
n79	600	4400–5000	4400–5000	TDD
n80	1 × 75	1710–1785	—	SUL
n81	1 × 35	880–915	—	SUL
n82	1 × 30	832–862	—	SUL
n83	1 × 45	703–748	—	SUL
n84	1 × 60	1920–1980	—	SUL
n86	1 × 70	1710–1780	—	SUL

Table 1.4 Spectrum bands for high frequency (FR2).

Operating band	Total spectrum	Uplink (GHz)	Downlink (GHz)	Duplex mode
n257	3 GHz	26.5–29.5	26.5–29.5	TDD
n258	3.25 GHz	24.25–27.5	24.25–27.5	TDD
n260	3 GHz	37–40	37–40	TDD
n261	850 MHz	27.5–28.35	27.5–28.35	TDD

Downlink), although one may observe that as of today none of the SUL bands are actually uplink only bands due to frequency regulation as in all cases the SUL band is actually the uplink portion of an FDD band, and the SUL designation is driven by a specific deployment idea within a band combination.

The 3GPP specifications are written in an agnostic way with respect to the carrier frequency, yet, the introduction of FR1 (frequency range 1) and FR2 (frequency range 2) terminology was needed to differentiate the cases where particular frequency range dependent operation is needed. There is no strong border line in terms of FR1 and FR2, but FR1 is mainly referring to the operation in bands below 6 GHz (this was extended to 7.125 GHz in 2019 for future compatibility) while FR2 is referring to the operation in bands in the range of 24.25–52.6 GHz. The background of these frequency ranges is related to the candidate frequency ranges for IMT use that the World Radio Conference (WRC) 2015 agreed to be studied for possible IMT identification. The WRC had a number of distinct frequency blocks that 3GPP lumped together. The later extension of the FR1 upper edge was to accommodate for a potential new unlicensed frequency block 5.925–7.125 GHz. For future compatibility 3GPP has already started to look at frequencies above 52.6 GHz as well as frequencies between FR1 and FR2. The >52.6 GHz frequency range will very likely get introduced as a new Frequency Range with some additional technology solutions to better optimize the radio system for these frequencies, while it is somewhat unclear if a new FR would be introduced between 7.125 and 24.25 GHz, or if FR1 and FR2 would be extended to close the gap. This will at least partially depend on what additional frequencies will be identified for cellular use in the future. The detailed operating bands and spectrum allocations for FR1 and FR2 are depicted in Figures 1.2 and 1.3 and also summarized in Tables 1.3 and 1.4.

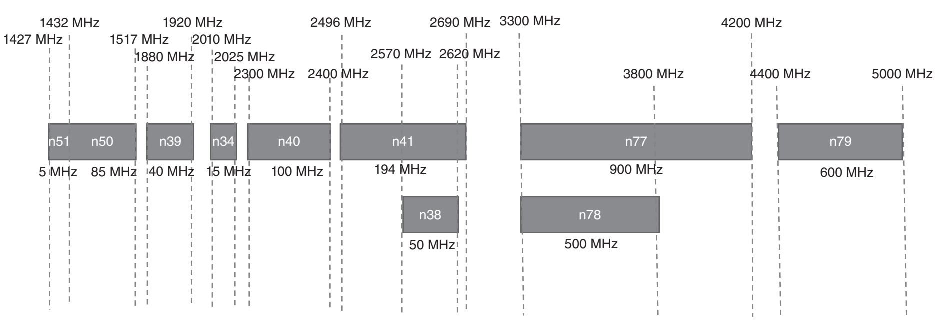

Figure 1.2 Spectrum bands for low-to-mid frequency (FR1).

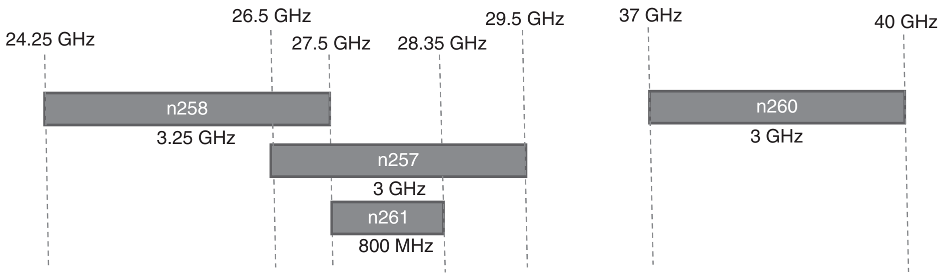

Figure 1.3 Spectrum bands for low-to-mid frequency (FR2).

1.3 Technology Components and Design Considerations

In its very beginning, the very first objective of the 5G was to identify and develop technology components needed for new radio systems being able to use any spectrum band ranging at least up to 100 GHz. The goal was to achieve a single technical framework addressing all usage scenarios, requirements, and deployment scenarios defined in TR38.913 [2], which was developed to also meet all the ITU-R requirements for IMT-2020 in ITU_R M.2410 [5]. One of the focus areas for the initial work related to defining fundamental physical layer signal structure for new RAT, the key topics including waveform, frame structure(s), and channel coding scheme(s). As one of the new physical layer building blocks for the new 5G, support for beam-based common control plane (CCP) in a massive MIMO framework was an important component. In LTE, dedicated control and data channels can be beamformed but support for common control plane beamforming was not provided, something which seems mandatory in the new system when moving to higher carrier frequencies.

The basic LTE Release 8 has been evolving with every release, adding in time new technologies and addressing new use cases. 5G NR has started with an ambitious plan of delivering a way more advanced basic package of techniques from its very first release (Release 15). Certainly, it is not feasible to have everything from the beginning, from both the perspective of not having enough time to create the specifications for the proposed techniques but also from the practical perspective of delivering products based on such techniques. Ideally, the evolution of the specification should go hand in hand with the market demand. Nevertheless, in the first stage of 5G discussions, a broad set of technology components and design guidelines have been on the design table, these being able to address the system requirements we have been discussed in a previous section.

- Large component *carrier bandwidth* is supported, ranging up to 400 MHz on FR2.
- *Multiple numerologies* are supported, since the system scales into very high carrier frequencies.
- While the *waveform is based on OFDM*, additional functionalities such as DFT-S-OFDM are supported. In a dedicated chapter of the book we are discussing also about the waveform variants which have been discussed and are considered in fact in 5G NR.
- A *flexible frame structure* is used to support the downlink and uplink of various techniques in FDD/TDD duplex arrangement. In addition, sidelink, and integrated access and backhaul (IAB) link are being considered as evolutionary steps on top of Release 15.

- All these are being supported for *standalone and non-standalone (NR anchored to an LTE carrier) operation*.
- *Enhanced massive MIMO* covering the analog/digital/hybrid beamforming is at the center of the physical layer design.
- New forms of access, such as *UL-grant free transmission* are supported.

The 5G NR has been designed in a forward compatible manner. Indeed, for example LTE suffers in various areas from the lack of flexibility, something the NR avoids already in its core design. The design principles building around forward compatibility have been considering:

- *Minimizing the transmission of always-on signals:* In LTE, the transmission of the always-on CRS is somehow problematic as even when a cell is empty, that particular cell transmits these signals and hence creates interference. The UEs' expectation for full bandwidth CRS also leads to rigidity of the utilized bandwidth. During the LTE evolution there have been solutions to alleviate this problem, such as turning off some of the CRS ports, in case the cell operates with four CRS ports, or developing techniques at the UE in order to mitigate the amount of interference created by the CRS. NR reference signals are designed mainly in a UE centric way while all of them have the possibility to be turned ON/OFF as needed by the system when there is no UE in the cell actually needing those signals.
- *All the signals and channels are confined within configurable time/frequency/spatial resources:* Such modular design, where we can imagine "tiles" of time/frequency/spatial resources containing different signals, possibly transmitted even with different numerologies, and multiplexed together in a seamless way. In legacy technologies it has been often difficult to handle signals which are transmitted in a wideband fashion and they need to be multiplexed with signals from other technologies which utilize a narrowband transmission. When such conflict happens, the only choice is to blank, in the overlapping area, one of the signals, typically the wideband one, and hence allow for a performance degradation of that channel. This is one situation NR avoids in its basic design.
- *Allowing for blanked resource which can be used flexibly in case of backward compatibility issues:* In every system it is important that the very first UEs designed for the system are able to understand such blanked resources which in future releases can be used by other techniques, not envisioned in the very first stage of the design. In other words, what is a blank resource for a Rel 15 UE may be a useful transmission for a later release UE.
- *User-specific bandwidth, waveform, and numerology*: Finally, in earlier cellular systems, the cell configuration is common to all UEs, and as a general principle, it does not vary in time. In NR, only the initial boot-strap needed for the UE to access the system is common. After that, each UE can operate with its own cell bandwidth (UE-specific bandwidth part [BWP]), uplink waveform can be selected between the CP-OFDM and DFT-S-OFDM, while in DL this is not possible not because the system flexibility wouldn't allow, but at the time of writing, there is only one DL waveform in the specifications. Also, the UE's subcarrier spacing and CP can be individually configured. Different combinations can exist at the same cell and one UE does not need to care of what some other UE is configured with. This flexibility by and large is not necessary and all UEs in the cell operate

with the same basic configuration for natural reasons, but it offers a natural growth path as whatever the current UEs are capable of doing does not restrict what the future UEs can do in the same system.

1.3.1 Waveform

Following the experience of LTE which is utilizing OFDM in downlink and DFT-S-OFDM in UL, the new radio system has considered the OFDM-based waveforms at least as a reference in its early design stage. Several design requirements were steering the waveform selection: the applicability of the technologies in a wider spectrum of carrier frequency and the range of deployment services identified in TR 38.913, including:

- Enhanced mobile broadband (eMBB)
- Massive machine-type-communications (mMTC)
- Ultra reliable and low latency communications (URLLC)

In such a mix of scenarios, it was clear that one needs to combine the choice of waveform with the choice of numerology in order to meet the requirements. Indeed, for short symbol durations one needs to utilize larger subcarrier spacings when targeting low latency services while for long symbol durations, smaller subcarrier spacings are a good choice for high delay spreads and multicast/broadcast services. As often it is the case, a compromise was needed in order to converge to a limited amount of choices which are feasible for implementation.

The targeted frequency bands are playing their role in the waveform selection. For FR1 and FR2 operation, waveforms of the OFDM family are a good choice in this frequency range, due to high flexibility in multiple access, good MIMO compatibility and low complex fast Fourier transform (FFT)-based implementations with scalar equalization. NR Release 15 is supporting CP-OFDM waveform for up to 52.6 GHz for both DL and UL transmission, while this is complemented by the utilization of DFT-S-OFDM based waveform in the uplink. CP-OFDM waveform can be used for a single-stream and multi-stream transmissions, while DFT-S-OFDM based waveform is limited to a single stream transmission (targeting for link budget limited cases). The multiplexing of different air interface configuration is mainly done in a frequency division multiple access (FDMA) manner which means that time or frequency domain filtering could be applied over parts of the carrier bandwidth in order to improve isolation between sub-band and to allow asynchronous communication or user specific numerology. A DL/UL symmetric utilization of CP-OFDMA is a good choice in providing the best capacity solution and localizing the waveform well in time, in order to achieve high capacity and hence allowing the utilization of higher order modulations. The efficient in-band multiplexing of different non-orthogonal waveforms/numerologies is defined by the in-band emission requirements which leads to good spectrum efficiency. Such implementation may be achieved by filtering, the requirements being specified by the standard while they are met in an implementation specific way by each manufacturer. Good spectral localization is driven by controlling efficiently the in-band (intra-carrier) adjacent channel leakage ratio (ACLR).

1.3.2 Multiple Access

The basic NR multiple access concept is TDM/FDM, where different users may be separated to transmit or receive by scheduling them to utilize a given frequency resource at different times. This concept of slotted access was used already in many 2G systems. In addition, the OFDM/DFT-S-OFDM system allows for scheduling different users to use a different frequency portion of the cell's frequency resource at the same time. This is familiar e.g. from LTE. Using a more formal terminology, the mechanism the UE uses to initially access the network is called *contention based* access, where different UEs' transmission attempts may collide with each other as the basic random access uses this access mechanism. Also, the uplink transmissions with configured grant, where the UE may start transmitting at any given time on pre-determined resources can be used in this way by configuring multiple UEs with the same resources to use when they have something to send. All other access mechanisms in NR are essentially *contention free*, the uplink and downlink transmissions are scheduled on resources orthogonal to those used for some other users.

Having the radio resources of the network being controlled by a dynamic scheduler it is something which legacy technologies are utilizing, this being the case of LTE. 5G NR has adopted also this strategy as it proves to be the most reliable way in meeting the users' QoS requirements, adapting to the radio conditions, etc. Indeed, the three families of applications considered in 5G, the eMBB, mMTC, and URLLC, are having diverse sets of requirements and these are best met based on network controlled scheduled resources.

1.3.3 Scalable/Multi Numerology

1.3.3.1 Motivation for Multiple Numerologies

The different 5G NR scenarios discussed so far in this chapter are having a direct connection to the 5G NR numerology design, as discussed in Table 1.5

In addition to different scenarios, TR 38.913 [9] describes the key performance indicators for the next generation access technologies. Many of them have a direct connection to the new radio numerology design. Table 1.6 summarizes the most important KPIs from the new radio numerology point of view.

Based on the 5G new radio scenarios and KPIs, there was a need for a common numerology framework to cover the full frequency range up to 100 GHz and support for all the envisioned environments/deployments and scenarios. One single numerology is clearly not sufficient to fulfill all the requirements, while a common framework significantly reduces not just the specification effort, but implementation effort as well, while maximizing the hardware commonality for different scenarios.

1.3.3.2 5G NR Numerologies

It is advantageous from an implementation point of view if the different options of scalable new radio numerology can be obtained utilizing the same common base clock. Thus, the need for scalability leads to all the 5G new radio sampling rates and corresponding subcarrier spacing being 2^N from the one base sampling rate.

Table 1.5 Scenarios impacting 5G new radio numerology.

Scenario	Requirements set for 5G new radio numerology
Support for different usage scenarios including • Enhanced mobile broadband • Massive machine-type-communications • Ultra reliable and low latency communications	• Support scalable numerology w.r.t. scenario.
Support for carrier frequencies up-to 100 GHz	• Support scalable numerology (e.g. the used bandwidth and subcarrier spacing, subframe length) w.r.t. carrier frequency: ■ Spectrum below 6 GHz is rather fragmented and composed of a mixture of bands for paired and unpaired operation. ■ As an outcome of WRC-15*, frequency bands between 24.25 and 86 GHz for IMT/5G, are studied for ITU-R WRC-19. ■ 28 GHz band (27.5–29.5 GHz), excluded from ITU studies, may have potential to become a de-facto 5G band in certain countries. ■ Other bands beyond WRC-19 may be identified in later WRCs or regional/national bodies • Co-existence and tight interworking between the new RAT and LTE require specific consideration especially in TDD scenario. Even though backward compatibility to LTE is not required, it is beneficial to utilize similar symbol timings especially on lower carrier frequencies, where LTE and new RAT may exist on adjacent carriers. One possible option for co-existence could be partial 5G re-use of LTE spectrum with MBMS subframes. Also in-band coexistence with LTE-M/NB-IoT for low frequencies (<2–3 GHz) should be supported. • Phase noise requires specific consideration in high carrier frequencies. It can be alleviated through larger subcarrier spacing and phase noise estimation and compensation.
Different deployment scenarios: • Indoor hotspot • Dense urban • Rural • Urban macro • High speed	• Support for scalable numerology w.r.t environment. • Smaller cell sizes imply lower delay spreads and hence allow shortening cyclic prefix (or other corresponding guard time) length. • Required CP duration may be assumed to be in the order of ~2 and ~4 μs, for the FDD and TDD WA cases respectively, with typical WA cell sizes. • Shorter TDD CP of ~2 μs is sufficient for dense urban deployments, given the typical values of excess delay spread in urban macrocells (e.g. 1.9 μs for the ITU Urban Macro cell channel model) with cell range limited below 1 km. • Even shorter CP of ~1 μs or smaller can be considered for small cells and in higher carrier frequencies.
Support for massive MIMO	• Support for RF beam switching within a subframe.

Table 1.6 Key performance indicators impacting the new radio numerology.

Key performance indicator	Definition [2]	Requirements set for 5G new radio numerology
Peak data rate Peak spectral efficiency	Obtained when all assignable radio resources for the corresponding link direction are utilized	Support for scalable numerology to minimize overhead and to maximize peak data rate/spectral efficiency in different scenarios.
Control plane latency	The time to move from a battery efficient state to start of continuous data transfer.	Support short subframe length(s)
User plane latency	The time it takes to successfully deliver an application layer packet from the radio protocol layer 2/3 SDU ingress point to egress point.	Support short subframe length(s)
Coverage	Definitions for mMTC type deep indoor coverage and long-distance communication coverage are still under discussion	Support long/concatenated subframe length(s)
Mobility	The maximum user speed at which a defined QoS can be achieved (in kmph). The target for mobility target should be 500 kmph.	Subcarrier spacing needs to be decided so that the influence of the Doppler effect can be managed with minimal performance degradation

Further, it i even more beneficial to reuse the same common base clock with LTE. Coexistence with LTE-TDD indicates that numerology evolvement from LTE and for example symbol level alignment between the new radio and LTE may be preferred especially with lower carrier frequencies. Thus, it is advantageous to be able to synthesize the new radio *sampling* rates utilizing the same common clock with LTE and to align the symbol length with LTE-TDD. Furthermore, to facilitate efficient implementation of multi-RAT base stations and multi-RAT fronthaul interfaces, using the same base clock is considered beneficial, hence the 5G new radio base clock rate is 2^N of the base sampling rate used in LTE.

TR38.913 requires at least dual-connectivity type of aggregation of LTE and 5G new radio data flows: "*Considering high performing inter-RAT mobility and aggregation of data flows via at least dual connectivity between LTE and new RAT. This shall be supported for both collocated and non-collocated site deployments*" [2]. The support of DC level aggregation of data flows in L2 benefits from synchronized sub-frame boundaries of the two RATs. In order to support common L2 that is seen as a good enabler for joint scheduling and efficient implementation, the 5G new radio subframe length is defined as integer division of 1 ms corresponding to LTE subframe. The key motivation for this was to allow for a phased introduction of NR, as the DC setup allowed for the radio-to-core network as well as the UE-to-core network protocols as they were, and the core network itself agnostic to the fact that an NR booster was added to the LTE architecture, and only in a later phase introduces

Table 1.7 5G new radio 5G PHY numerologies for OFDM based waveforms.

Spectrum band	**<6 GHz**			**3…40 GHz**	**20…100 GHz**	
Maximum carrier bandwidth (MHz)	**5**	**20**	**100**	**200**	**400**	**1600**
Waveform	OFDM/SC-FDMA (/UF-OFDM)			OFDM	OFDM	ZT-S-OFDM
Clock rate (Mchip s^{-1})	Up to 30.72	30.72	122.88	245.76	491.52	1966.08
Sub-carrier spacing (kHz)	3.75	15	60	120	240	960
Ts (μs)	266.67	66.67	16.67	8.335	4.17	1.04
Maximum (I)FFT size[a)]	16–2048	2048	2048	2048	2048	2048
# symbols per subframe	FFS[b]	7	7	14	28	120
Sub-frame length (μs)	FFS[b]	500	125	125	125	125
CP (μs)	19.2	4.8	1.2	0.6	0.3	—
CP overhead (%)	6.7	6.7	6.7	6.7	6.7	—

a) Implementation issue, not to be standardized, however standard needs to support efficient implementation. (I)FFT size higher than 2 K FFT is not seen feasible from implementation point of view.
b) The length of the sub-frame is to be defined.

a full-blown 5G core network and the corresponding network and UE protocols that are needed to come with it.

Larger subcarrier spacing of NR offers increased robustness to the higher phase noise as well as an option for keeping the FFT size reasonable when carrier bandwidths are increased. The amount of available bandwidth increases as a function of increasing carrier frequency, leading also to larger carrier bandwidths. Carriers up to 100 MHz may be available at the conventional <6 GHz cellular spectrum area for eMBB communication. For lower frequencies, the 15 kHz subcarrier spacing is a feasible baseline for large micro-cell deployments needing the long CP. For 20–60 GHz frequency range, carrier bandwidths ~200 MHz or more can be expected, whereas for >60 GHz they are expected to be even larger, possibly over 1 GHz. In order to keep the system design and implementation complexity in feasible limits, fully flexibly adjustable numerology is not preferred due to high number of cases to define requirements for implementation and testing. Hence, a limited set of possible numerologies covering the different spectrum areas and scenarios is more practical.

For example, the supported 5G new radio PHY numerologies and waveforms is presented in Table 1.7. In addition to the parameters listed in the table, also Physical Resource Block (PRB) size was assumed to be scalable in a similar manner. It can be seen that the proposal was not too far from what was eventually specified for NR Release 15, while some significant differences can be observed as well. One reason for many of the original proposals having a lot of common ground was an extensive research collaboration under several public–private–partnership research frame works as well as some of the need for LTE compatibility related aspects, as explained earlier, being universally common.

1.3.4 Multi-antenna

Larger antenna arrays in terms of number of antenna elements are required at higher carrier frequencies to compensate increasing path loss between transmitter and receiver. As the carrier frequency increases, a single antenna becomes smaller and captures a smaller surface area of the radio propagation sphere, or conversely a fixed area (panel) can accommodate a larger number of physical antennas. On the other hand, the number of transceiver units cannot easily be increased mainly due to cost and energy consumption of the transceiver units (power hungry converters). Thus, from a technology point of view it can be noted that the NR designed to operate across carrier frequencies up to 100 GHz will need to support a variety of different transceiver and antenna system architectures at the BS side. These architectures can be categorized at a high level into fully digital, hybrid, and fully analogue beamforming systems. The architecture types with their characteristics are depicted at a high level in Figure 1.4.

Typically, fully digital transceiver architectures can be expected to be utilized in the lower end of the 5G spectrum where number of antennas is limited, and bandwidth is relatively low, hybrid architectures may be utilized in higher spectrum bands to keep the number of transceiver units in a cost and power efficient realm while providing support for a higher number of antennas. Fully analogue beamforming architectures are the extreme simplification of the hybrid setup with just a single transceiver unit and could be used to minimize the product cost in the very high end of the new radio spectrum. Furthermore, it is expected that a similar tendency in transceiver and antenna architecture can be considered for the UE side as well as in the base station. However, it is to be noted that architecture selection is vendor specific and thus no strict applicable carrier frequency range can be defined for different architectures. More detailed description of such techniques is described in further sections of this book.

Beamforming techniques are thus the centerpiece of the 5G NR design. When operating in lower carrier frequencies common control plane signaling (referred here as downlink synchronization signal(s), system information transmission in broadcast manner and paging, and random access channel [RACH] in uplink) may be based on wide sector beams at BS for transmission and reception. On the other hand, as discussed above, coverage enhancement will be particularly important at higher carrier frequencies, where the

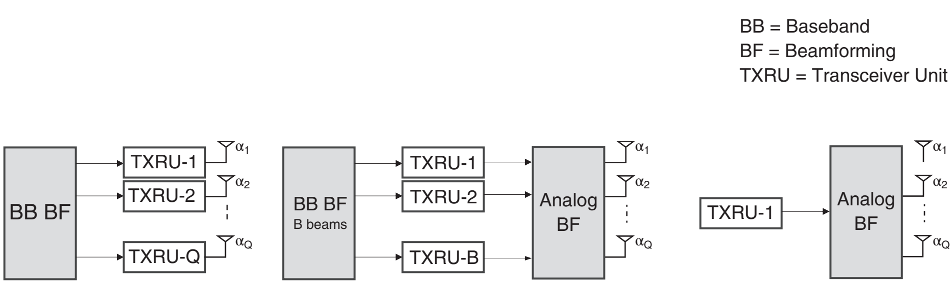

Figure 1.4 Examples of different transceiver and antenna system architectures: left: fully digital, middle: hybrid, right: fully analogue architecture.

deployments will tend to be mostly coverage limited due to the poor path loss conditions. Severe coverage limited situations pose difficulty that can be overcome with massive MIMO: a sector-beam type of approach for the common control signaling may not be feasible since there wouldn't be sufficient gain to achieve the needed cell radius. Therefore, to improve the cell radius a sweeping narrow beam approach is essentially a requirement for the common control. In a beam-based common control scheme the gNB transmits downlink and receives common control signals and channels via narrow beams in sweeping manner throughout the cell. In general, common channel beamforming can be used by the system when needed in all frequencies to improve coverage and cell detection.

The content of this book tries to focus on the utilization of beam-based operation in 5G NR. Naturally, the whole design, starting from initial access to transmitting and receiving data, must take this into account. The utilization of beams is generating quite a new system design approach, as one needs to encompass the challenges accounting for such operation, these ranging from achieving a reasonable latency when accessing the system, to an efficient power consumption for the UE, etc.

1.3.5 Interworking with LTE and Other Technologies

One core requirement was tight interworking with LTE. The way this was realized was a dual connectivity solution with the LTE carrier as the anchor cell to which the NR carrier is attached as a secondary cell, and the user plane data flows are connected at the Packet Data Convergence Protocol (PDCP) layer. The 3GPP supported architecture options allowing for either of the two radios to act as the master node, and the core network connection can be toward the 4G Evolved Packet Core (EPC) core as well as the 5G core network. The primary architecture that was designed to enable fast NR roll-out is leveraging the existing LTE deployments and 4G EPC core network by attaching the NR cell as a secondary cell to the existing LTE/EPC deployment. Figure 1.5 depicts the high-level view of this architecture option, while the full set of architecture options are discussed in more detail in Chapter 2.

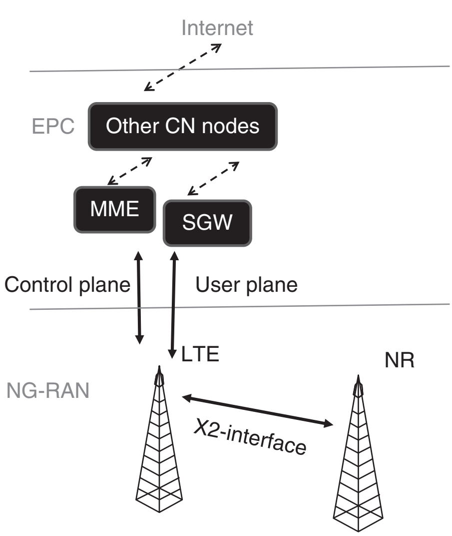

Figure 1.5 LTE-NR tight interworking architecture optimized for fast roll-out.

In this LTE-NR Dual Connectivity setup the UE is connected to both the LTE and the NR base stations and two radios operate independently on physical and Medium Access Control (MAC) layer and the data flow split is made in the PDCP layer. The user plane data flow can also be routed directly from the EPC to the NR base station rather than via the LTE base station.

An LTE-NR Dual Connectivity deployment can later be evolved to a stand-alone NR system with more traditional inter-system mobility between the NR and LTE, and the deployment can appear as a stand-alone NR system for the UEs supporting that and LTE-NR DC deployment for the UEs that do not support the stand-alone NR mode of operation. The NR Release 15 supports inter-technology handovers to (and from) LTE, while Release 16 is working to introduce NR-to-UMTS handovers (but not the other way around), and the mobility back to NR is based on cell reselection after the call has been released. NR – Wi-Fi interworking has no special support in the NR Release 15 specifications, and if the UE supports them both, the two technologies operate independently of each other with no traffic steering support, although it is likely that some interworking features will be specified in future releases of the 3GPP specifications.

1.3.6 5G Beam Based Technologies Across Release 15 and Release 16

The first release of 5G NR, Release 15, introduces basic system functionality, the main components being mentioned in the previous chapter. To state these again, the system is based on OFDM in downlink and on OFDM and SC-FDMA in uplink, operates with multiple numerologies across a vast amount of carrier frequencies spanning from 600 MHz up to 52 GHz, while MIMO functionality is possible in any deployment, in fact the MIMO functionality is a basic functionality on all bands, and in deployments above 3.5 GHz beamforming is assumed to be commonplace as everything happens through “beams.” In the first release, the system design has focused more on the traditional single transmission point operation, that is the UE connects to a transmission point (cell) and the data exchange takes place in this way. Additionally, the dual connectivity to LTE and NR is also possible, and in future, UE connection to multiple 5G transmission points either in a dual connectivity setup, or as a single cell's multi-panel configuration similar to multi-point MIMO. 5G intends to serve a large amount of application areas, so called verticals, and hence technology components are added on top of the main functionality designed in Release 15. In the following we briefly describe the upcoming technologies.

1.3.6.1 Integrated Access and Backhaul

IAB has the scope of enabling an integrated solution for providing access and backhaul links over the same carrier frequency. Indeed, 5G NR promises highly increased DL and UL availability, however, such massive data communication may be too expensive to deploy using traditional wired or dedicated point-to-point wireless backhaul links. IAB is a practical answer to such questions and such technology is facilitated by the existence of massive MIMO as a basic building block of the system. An example of IAB deployment is presented in Figure 1.6 where the IAB nodes can multiplex the access and backhaul data traffic in both time, frequency and/or space.

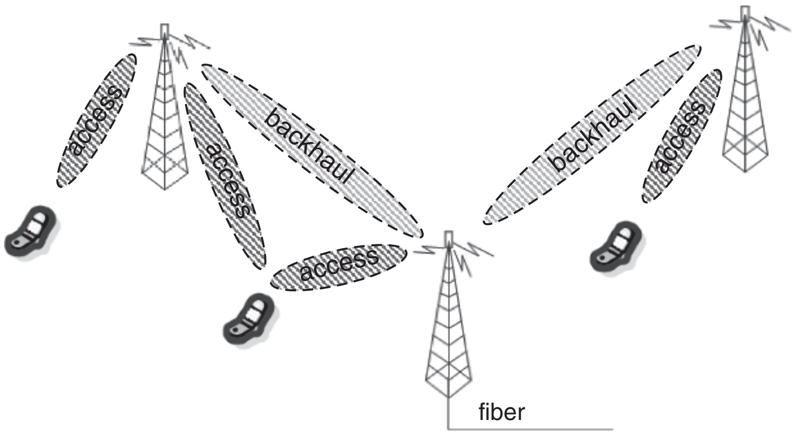

Figure 1.6 Illustration of integrated access and backhaul.

Initial access is a first area where IAB is expected to need particular enhancements as there is a need for orthogonal SSB to the SSB used for UEs. RACH design is also one area of development as there is expected to be a need for extending the RACH occasions and periodicities for backhaul RACH resources w.r.t the RACH resources. Resource multiplexing is a key area of design as we area dealing with both backhaul and access links.

1.3.6.2 NR Operation on Unlicensed Frequency Bands (NR-U)

Spectrum and its availability are critical enablers of communication technologies. We have previously mentioned in this chapter the spectrum utilization in 5G, however, while the licensed spectrum remains superior from the QoS point of view as it provides seamless coverage and highest reliability and spectral efficiency, it is of critical importance to provide 5G NR functionality in the area of unlicensed spectrum as well, this being possible by either with so called Licensed Assisted Access (LAA) carriers that are paired with anchor carrier on a licensed band, or with a fully stand-alone deployments in unlicensed spectrum. Thus, 3GPP targets a single global solution for access to unlicensed spectrum, the considered operation being in the bands of 5 and 6 GHz, but some band and regional differences in how the unlicensed operation is allowed requires some flexibility in the solutions to be specified. Co-existence with other technologies occupying the same unlicensed spectrum is of critical importance and governed by specific regulations, like for example in 5 GHz where there are already Wi-Fi deployments.

Channel access mechanisms are of critical importance in NR-U. Initial access is an area where the baseline specification of Release 15 needs to be extended as NR-U has its own channel access particularities and the number of candidate SS Blocks might need to be increased in order to lead to reliable discovery. Other particularities of the physical layer and procedures relate to the design of the frame structure and of the discovery reference signal, the possible extension of the physical random access channel (PRACH) formats to support the minimum bandwidth requirement given by the regulations. The DL and UL control channel design as well as the transmission of PDSCH and PUSCH are areas of investigation as well. The functions of radio link monitoring (RLM)/radio link failure (RLF) may need to be extended due to reduced transmission opportunities for DL signals.

1.3.6.3 Ultra-Reliable and Low Latency Communications

URLLC provides a key platform for various application areas from which we name a few: electrical power distribution, factory automation, transport industry where the focus is on the information exchange between a UE supporting V2X and a V2X application server, augmented reality, virtual reality (entertainment industry). The common denominator of these enumerated application areas are the need for high reliability for various degrees of latency bounds ranging from 1 ms air interface delay for AR/VR to 15 ms in the case of power distribution. One of the main goals of 5G NR was to provide native support for URLLC. In this respect, Release 15 contains several basic URLLC enablers such as slot structure facilitating low latency as well as other components enabling improved reliability. URLLC targets the operation across all frequency bands, including the beam-based operation in FR2. However, the main focus is on enhancing the control channel design, enhancing the uplink control information (UCI) operation, improving PUSCH for both grant based and configured grant (grant free) operation, improving the scheduling/hybrid automatic repeat request (HARQ) in the direction of low latency support.

1.3.6.4 Vehicular-to-everything (V2X)

3GPP/LTE has already a tradition in providing a platform to automotive industry as the support of V2V already exists in LTE since Release 14 2016, while further integration in the cellular environment has happened in V2X. The range of applications for V2X is quite vast, out of the identified 25 use cases we highlight the following:

Extended Sensors is perhaps one application area with a potential immediate impact for a large number of drivers. In this case the vehicle collects information based on installed sensors and exchanges this information based on V2X application servers. The use of extended sensors enable other application areas such as *advanced driving* which can be semi or fully automated and where the exchange for data between vehicles can lead to collision avoidance and improved traffic efficiency.

Vehicle Platooning implies a dynamically formed group of vehicles moving together. The lead vehicle stands as the main source of information for the rest of the vehicles from the group. Obviously, the latency of the communication between the vehicles is rather small, while the reliability needs to be also high.

The V2X communication links are a bit different from the communication of the UE with the gNB. This technology enables the communication of the devices directly between each other, this being called a sidelink. Such sidelink communication can be unicast (a connection between two UEs) or sidelink groupcast (a one-to-many sidelink message) or sidelink broadcast (a one-to-whoever can hear sidelink message). V2X operation is envisioned for both FR1 and FR2. While no particular design is attempted or FR2 with respect to the beam management part, it is expected that the basic Release 15 “beam based” functionality will be used.

Some of the physical layer expected specification areas include the synchronization mechanism, the resource allocation strategies, HARQ, channel state information (CSI) acquisition, and power control.

1.3.6.5 Positioning

Providing accurate positioning to the 5G NR UEs is of key importance in today's world. Accurate positioning is possible based on many technologies such as GNSS or radio based (LTE and Wi-Fi networks, etc.), however, 5G NR has the benefit of supporting a large array of antennas at the base station as well as indoor and outdoor deployments facilitating the UEs localization in a wide range of scenarios. Positioning techniques need to operate in all NR deployments, hence in higher carriers as well. Accurate positioning boils down to the transmission of reliable reference signals whose measurements are providing a very good input in determining the location of the device. While Release 15 5G design has defined a good set of reference signals, these have not been considering the support for positioning techniques, hence one needs to investigate if additional reference signals design is needed from the perspective of utilizing both the downlink and the uplink reference signals.

1.3.6.6 System Enhancements

1.3.6.6.1 2 Step RACH Low latency initial access is a high incentive for any radio system. While the current 5G design is based on a four steps RACH operation, it is believed that two step RACH can bring potential benefits for channel access in several application areas such as mMTC, URLLC, and eMBB and for both licensed and unlicensed operation.

1.3.6.6.2 Cross Link Interference Mitigation (CLI) Cross link interference (CLI) is an inherent problem of unsynchronized TDD operation and in some circumstances can require particular attention when handling communication beams. Indeed, in high carrier frequencies, advanced MIMO techniques can be utilized to mitigate cross-link interference.

1.3.6.6.3 UE Power Saving Efficient battery life is an undisputed essential component of any device. Release 15 NR consists of power saving mechanisms such as Discontinuous Reception (DRX) and BWP adaptation. Ultimate power saving mechanisms are targeting the adaptation/finetuning of UE operation on a wide range of characteristics such as the dynamic adaptation of the MIMO layers, the efficient scheduling procedure, the efficient utilization of the control channel.

1.3.6.6.4 Mobility Enhancements Release 15 NR design is based on a basic mobility mechanism where a source gNB triggers handover by sending HO request to target gNB and after receiving ACK from the target gNB, the source gNB initiates handover by sending HO command with target cell configuration. The UE sends PRACH to the target cell after radio resource control (RRC) reconfiguration is applied with target cell configuration. In high carriers of FR2, due to the need of beam sweeping, the HO can incur larger interruption time compared to lower carrier frequency deployments or to the LTE. The sensitivity to beam, due to beam blockage or UE rotation, is another reason for looking into enhancements in the mobility area. Identifying handover solutions to achieve high handover performance with 0 ms interruption, low latency, and high reliability is of great importance.

1.3.6.6.5 MIMO Enhancements MIMO is a basic system component of 5G NR, not only a capacity enabler. MIMO techniques are in a continuous evolution, either from the perspective of increasing system capacity where CSI feedback is a critical component, or from the perspective of increasing beam management reliability in higher carriers. The basic NR MIMO framework allows for an easy introduction of new MIMO enhancements without disrupting the MIMO operation with existing device base, both through network implementation innovation as well as additional improvements requiring also UE support.

1.3.6.6.6 Support for Above 52 GHz Frequencies While 5G NR is promises to harvest a wide range of spectrum, Release 15 5G design fits carrier frequencies up to 52.6 GHz. Frequencies above 52.6 GHz are very likely requiring a new DL waveform solution likely in the form of low peak-to-average power ratio (PAPR) single carrier operation, something which is already possible in UL. The propagation characteristics in these bands are more challenging due to high atmospheric absorption, lower power amplifier efficiency, and strong power spectral density regulatory requirements. However, the incentive is also high as potential for wider bandwidths, this fitting the need for a wide range of use cases such as V2X, IAB, NR licensed and unlicensed, and even non-terrestrial operations.