Chapter 1
Introduction to 5G and Beyond

Xingqin Lin and Namyoon Lee

1.1 Book Objective

Over the last 40 years, mobile communications services have witnessed explosive growth. The first commercial cellular telephone system in the United States, known as advanced mobile telephony system (AMPS), was placed into operation in late 1983. Today, mobile communications services are ubiquitous and used by a large percentage of the world's population. According to Ericsson Mobility Report [1], as of Q3 2019 we have 5.9 billion subscribers and 8 billion subscriptions in the world. The total number of mobile subscriptions now exceeds the world's population.

Appreciating the evolution of mobile communications systems is important for understanding how modern mobile communications systems are now able to deliver the services at the remarkable scale. A new generation of mobile communications standards has appeared about every tenth year, with the first generation (1G) being introduced in the 1980s. From 1G to the third generation (3G), mobile voice telephony was the main application driving the growth of mobile communications systems. Since 3G, mobile broadband data applications have become the main force for further evolution of mobile communications systems. Today, the *Long-Term Evolution* (LTE), representing the fourth generation (4G) of mobile communications systems, has been widely deployed to deliver mobile broadband data services. While the mobile voice telephony and mobile broadband data services remain the primary applications of mobile communications systems, new applications for the Internet of Things (IoT) and the Fourth Industrial Revolution start to help further drive the

X. Lin (✉)
Ericsson, Santa Clara, CA, USA
e-mail: xingqin.lin@ericsson.com

N. Lee
Electrical Engineering, Pohang University of Science and Technology (POSTECH), Pohang, Gyeongbuk, Korea
e-mail: nylee@postech.ac.kr

X. Lin, N. Lee (eds.), *5G and Beyond*, https://doi.org/10.1007/978-3-030-58197-8_1

future growth of mobile communications systems, including the fifth-generation (5G) wireless access systems.

The transition from 4G to 5G will support more diverse usage scenarios and applications. The International Telecommunication Union's Radiocommunication Sector (ITU-R) has defined three areas of usage and applications in the 5G era: enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine type communications (mMTC) [2]. While the evolution of LTE will have the capability to support a wide range of usage scenarios and applications in the 5G era, there is a need for a new generation of mobile communications systems that incorporate more advanced technology solutions to achieve higher data rates, lower latency, greater capacity, and more efficient spectrum utilization [3]. Equipped with these more advanced capabilities, the next-generation wireless access technology *New Radio* (NR), the main subject of this book, is the key enabling technology for supporting the diverse usage scenarios and applications envisioned for the 5G era.

5G will bring enormous socioeconomic benefits. The heart of 5G NR is a set of fundamental technologies, making 5G capable of providing much more efficient networks, enabling new services, new ecosystems, and new revenues. The technologies continue to be evolved to further expand the 5G ecosystem and transform vertical industries. The main objective of this book is to provide a comprehensive treatment of the 5G mobile communications systems. This book will cover both the fundamentals and the state-of-the-art of the 5G NR standards. Now 5G systems are being switched on. A substantial portion of the book will be devoted to the next-generation wireless access system (6G) to discuss the technologies that will come next.

The next sections give more sense of the intended scope of this book. We first provide an overview of the evolution of mobile communications systems from 1G to 4G. We then elaborate more on what 5G is through discussing the main technical requirements behind 5G, the main 5G use cases, and the key ingredient technology components that enable the advanced 5G capabilities. Next, we describe the 5G standardization process and key organizations that are essential for defining what 5G is. The following section provides a brief look into 6G – the next-generation wireless access system. We close the chapter with outlining the contents of the remaining chapters of this book.

1.2 Evolution of Mobile Communications Systems Before 5G

Mobile communication systems have significantly changed our lives. They eliminate the limitations in time and space to transfer information from one place to another. This allows people to exchange or access information whenever, whatever, and wherever they want. Mobile communication systems now have become an essential part of our lives.

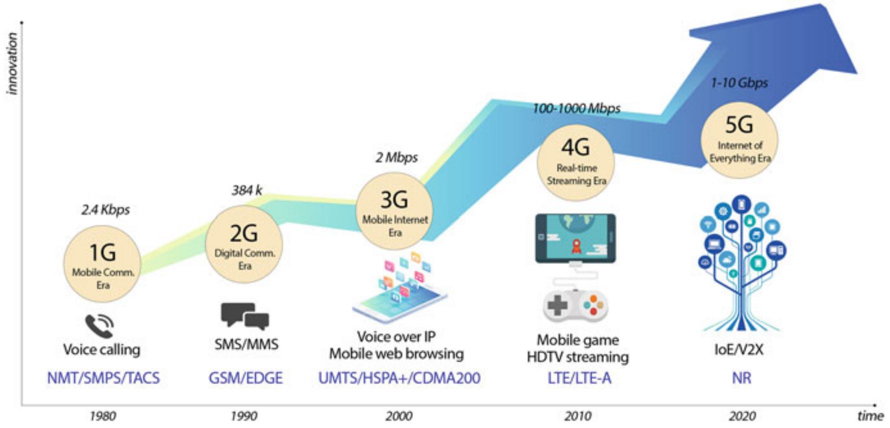

Fig. 1.1 Evolution of mobile communication systems

Mobile communication systems have evolved over several decades. To fully understand where we are in 5G, we need to retrospect what we have developed from the revolutionary 1G to 4G and reflect what has fundamentally changed from one generation to the next (Fig. 1.1).

1.2.1 1G: Analog Mobile Communication Era

1G opened a new mobile communication era. Historically, the initial idea of a cellular system was proposed by Bell Labs in 1947. This idea was commercialized by Nippon Telegraph and Telephone (NTT) in 1979. In early 1980s, the Motorola also released one of the first mobile phones called “DynaTAC” to provide the 1G mobile communication service. Different countries developed their own 1G standards, including Nordic Mobile Telephone (NMT) used in Eastern Europe and Russia, AMPS used in North America, TACS (Total Access Communications System) in the United Kingdom, and TZ-801/2/3 used in Japan.

1G adopted analog communication technologies using about 150 MHz carrier frequencies, and it only offered voice calls services. Although it paved a new way to eliminate the constraint in space for person-to-person communications, 1G had several shortcomings. The communication quality and security level were very low because of the inherent limitation of analog communication technologies. In addition, there was no compatibility across different mobile communication systems because each country developed its own system.

1.2.2 2G: Digital Mobile Communication Era

2G commenced a *digital* mobile communication era. The primary change from 1G was to use digital communication technologies instead of the analog ones. Digital communication technologies significantly improved the quality of communications and the security level, thanks to the power of digital systems. 2G was more than just person-to-person voice communication services. It supported transfer of digitally encrypted messages, including not only voice messages but also send text messages (SMS), picture messages, and multimedia messages (MMS). The numerous message types enriched business opportunities; thereby, the popularity of mobile communication systems exploded in this era.

The first 2G standard was the Global System for Mobile Communications (GSM), which was initially launched in 1991. The GSM supported the data rate of 9.6 kbit/s, and it evolved to General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE), which provided the maximum data rates of 40 and 384 kbit/s, respectively. GSM-based 2G standards adopted time division multiple access (TDMA).

1.2.3 3G: Mobile Internet Era

3G opened the *mobile Internet era*. A big innovation in 3G was the use of *data packet*-based communication technologies. The packet-switched communication technologies offered connectivity to the world wide web, i.e., the mobile Internet, from any location in the world using mobile communication systems. The maximum data rate of 3G was about 2 Mbps, which is approximately four times faster than 2G. This data rate enhancement made possible new services, including voice over IP (e.g., Skype), fast web browsing, and video streaming/conferencing. In this era, an innovative mobile device called *smartphone* was launched, such as the Blackberry in 2002 and the iPhone in 2007. This device expanded the service capabilities of the mobile communication systems.

3G was designed to meet the requirements of International Mobile Telecommunications 2000 (IMT-2000) standards. The first 3G service was launched by NTT DoCoMo in 2001 using the Universal Mobile Telecommunications System (UMTS) system standardized by the 3rd Generation Partnership Project (3GPP). This system evolved to HSPA+, which can yield the uplink and downlink peak data rates up to 28 and 56 Mbit/s, respectively. The Code Division Multiple Access (CDMA) 2000 system was the commercially successful 3G standard in North America and South Korea, standardized by 3GPP2. The follow-up standard, EVDO Rev B standard, enhanced the peak downlink data rates up to 14.7 Mbit/s.

1.2.4 4G: Real-Time Streaming Era

4G started off the *real-time streaming era.* The primary change from 3G to 4G was to provide extremely enhanced data rates up to hundreds of megabit per second. This data rate enhancement stimulated new mobile services, including real-time mobile gaming and high-definition mobile TV. The core technology in improving the data rates was a new multiple access technique, referred to as orthogonal frequency-division multiple access (OFDMA). In addition, multiple-input multiple-output (MIMO) communications technologies further improved the data rates up to an order of magnitude. These two core technologies fundamentally changed the design principles of cellular systems to overcome the channel fading and interference obstacles in wireless environments.

The commercial 4G LTE service was initially offered in Sweden 2009 and spread later in most countries of the world. For example, South Korea and the United Kingdom launched the LTE service in 2011 and 2012. The maximum downlink and uplink data rates of LTE systems are 100 and 50 Mbit/s when using a 20 MHz channel, respectively. This LTE system was enhanced by the follow-up standard, LTE Advanced (LTE-A). LTE-A was standardized in 2010 as part of Release 10 of the 3GPP specification. It used more spectrums and antennas to increase data rates further. LTE-A offered the data rates up to 1000 and 500 Mbit/s in downlink and uplink, respectively. Coordinated multipoint transmission and carrier aggregation technologies were the key ingredients to boost the system capacity.

1.3 What is 5G?

Previous generations of mobile communications systems (1G to 4G) predominantly addressed consumer demands for mobile voice telephony and mobile broadband data services. 5G is the next generation of mobile communications systems [4]. It builds on the successes of the previous generations of mobile communications systems. 5G promises to deliver improved end-user experience and enable new services, new ecosystems, and new revenues.

1.3.1 5G Use Cases

5G is expected to deliver much higher data rates, lower latency, greater capacity, and more efficient spectrum utilization. Equipped with these more advanced capabilities, 5G can support diverse usage scenarios and applications. ITU-R has defined three categories of potential use cases for 5G networks [2], eMBB, URLLC, and mMTC, which are illustrated in Fig. 1.2.

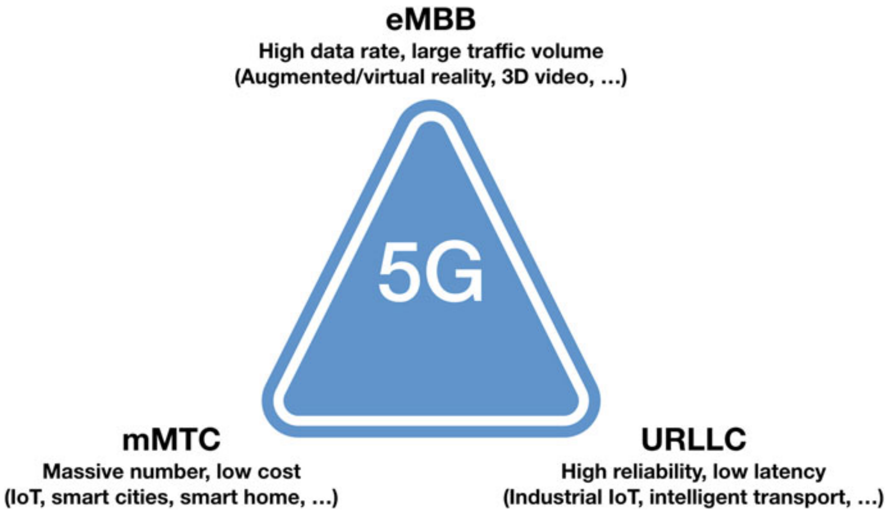

Fig. 1.2 5G usage scenarios

eMBB is a natural evolution of mobile broadband data services that remain the primary applications of mobile communications systems. It is characterized by high data rates and large traffic volumes. Example eMBB services include augmented and virtual reality, high-definition three-dimensional (3D) videos, and 4K streaming. 5G will deliver improved consumer experience by supporting high-speed mobile connectivity for eMBB applications. eMBB may also include applications in enterprise collaboration services.

URLLC corresponds to services require ultra-high reliability and low latency. One exemplary application is wireless control of industrial manufacturing and production processes. The high reliability and low latency characteristics will also be key for traffic safety and control in intelligent transport systems.

mMTC mainly refers to the IoT services that are characterized by a massive number of devices. Example IoT applications include smart cities, smart home, utilities, and remote monitoring. Key requirements of such services include low device complexity, long battery life time, and significant coverage extension, in addition to the support of a massive number of devices. Such services usually have relaxed latency requirements, and each device typically does not require support of high data rates.

There exist more scenarios and applications in the 5G era that may not strictly fall in the three defined categories of eMBB, URLLC, and mMTC. For example, some operators are using 5G as a last-mile access technology to homes. 5G fixed wireless access can help replace the costly deployment of fiber connections to homes. Similarly, mobile voice telephony is still an important application in 5G mobile communications systems, but it requires neither high data rate, nor ultra-high reliability, nor low latency.

1.3.2 5G Technical Requirements

In early 2012, ITU-R started a program, known as IMT-2020, to develop International Mobile Telecommunications for 2020 and beyond [2]. IMT-2020 defines technical performance requirements for 5G, which are summarized in Table 1.1.

Compared to 4G, 5G will increase data rates by 10 times. Specifically, 5G is expected to offer 20 Gbps peak data rate in the downlink (DL) and 10 Gbps peak data rate in the uplink (UL). In dense urban environment, 5G can support user experienced data rate (at the five percentile) of 100 Mbps in the DL and of 50 Mbps in the UL. With the dramatically increased data rates, 5G will deliver much enhanced mobile broadband experience.

5G spectral efficiency is expected to be much increased, with peak spectral efficiency reaching 30 bps/Hz in the DL and 15 bps/Hz in the UL. Different user spectral efficiencies can be supported in a variety of environments for eMBB. For example, in rural areas, 5G can support 0.12 and 0.045 bps/Hz user spectral efficiencies in the DL and UL, respectively, while in indoor hotspot, 0.3 and 0.21 bps/Hz user spectral efficiencies can be reached in the DL and UL, respectively. Accordingly, the DL area traffic capacity in indoor hotspot can reach 10 Mbps/m^2. Overall, 5G spectral efficiency is improved by 3 times compared to 4G.

5G is expected to be able to provide 1 ms user plane latency, which reduces the 4G user plane latency by 10 times. The much improved latency performance can meet the stringent latency requirements of industrial IoT and autonomous transport. In addition, 5G promises much improved reliability performance. In urban macro environment, it is expected that the success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coverage edge can reach 99.999%.

5G is expected to significantly improve mobility performance. It will provide 0-ms mobility interruption time. 5G can support satisfactory quality of service for mobility speed as high as 500 km/h.

5G is expected to support a connection density of 1 million devices per square kilometer. This greater capacity of 5G is well suited for meeting the requirements of mMTC scenarios.

Energy consumption is also a key consideration. 5G is expected to have high network energy efficiency with support of a high sleep ratio and long sleep duration.

1.3.3 5G Technology Components

While previous generations of mobile communications systems (1G to 4G) were very much radio focused, the entire system of 5G will be transformed to achieve much more efficient networks and enable new services, new ecosystems, and new revenues.

Table 1.1 Summary of 5G key technical requirements

Metric	5G target	Usage scenario
Peak data rate	DL: 20 Gbps; UL: 10 Gbps	eMBB
Five percentile user experienced data rate	DL: 100 Mbps; UL: 50 Mbps	eMBB: dense urban
Peak spectral efficiency	DL: 30 bps/Hz; UL: 15 bps/Hz	eMBB
Five percentile user spectral efficiency	DL: 0.3 bps/Hz; UL: 0.21 bps/Hz	eMBB: indoor hotspot
	DL: 0.225 bps/Hz; UL: 0.15 bps/Hz	eMBB: dense urban
	DL: 0.12 bps/Hz; UL: 0.045 bps/Hz	eMBB: rural
Average spectral efficiency per transmission reception point	DL: 9 bps/Hz; UL: 6.75 bps/Hz	eMBB: indoor hotspot
	DL: 7.8 bps/Hz; UL: 5.4 bps/Hz	eMBB: dense urban
	DL: 3.3 bps/Hz; UL: 1.6 bps/Hz	eMBB: rural
Area traffic capacity	DL: 10 Mbps/m^2	eMBB: indoor hotspot
User plane latency	4 ms	eMBB
	1 ms	URLLC
Control plane latency	20 ms	eMBB/URLLC
Connection density	1,000,000 devices per km^2	mMTC
Success probability	99.999%	URLLC: urban macro
Normalized channel link data rate	UL: 1.5 bps/Hz for mobility speed up to 10 km/h	eMBB: indoor hotspot
	UL: 1.12 bps/Hz for mobility speed up to 30 km/h	eMBB: dense urban
	UL: 0.8 bps/Hz for mobility speed up to 120 km/h	eMBB: rural
	UL: 0.45 bps/Hz for mobility speed up to 500 km/h	eMBB: rural
Mobility interruption time	0 ms	eMBB/URLLC

Radio Access Network

3GPP, a global standard-development organization for mobile communications, has developed a new wireless access technology known as NR. NR is the foundation for 5G radio access networks [5]. Key NR features are summarized as follows:

- Spectrum flexibility: NR supports operation in the spectrum ranging from sub-1 GHz to millimeter wave bands. 5G NR is the first mobile communications standard that supports operation in millimeter wave bands. Utilizing the large chunks of millimeter wave spectrum enables 5G to deliver multiple gigabit-per-second data rates and also can help mitigate the current spectrum crunch in sub-6 GHz. As in the previous generations of mobile communications systems, operation in sub-6 GHz frequency bands is vital in 5G to provide wide-area coverage. With interworking between high (millimeter wave) and low (sub-6 GHz) frequency bands, 5G NR can enjoy the speed and capacity increases from using high bands and focus on using low bands more for coverage purpose.

- Flexible duplex options: NR supports flexible duplex options including frequency division duplex (FDD), time division duplex (TDD) with semi-statically configured UL/DL configuration, and dynamic TDD. While FDD is often adopted in low-frequency bands where spectra allocations are often paired, TDD becomes increasingly common for higher-frequency bands with unpaired spectra. For large over-the-rooftop cells, semi-static TDD is suitable for handling inter-cell interference issues. Compared to 4G LTE that only supports FDD and semi-static TDD, 5G NR additionally introduces the support of dynamic TDD. In TDD spectrum, for small/isolated cells, dynamic TDD offers the possibility of dynamically allocating radio resources to adapt to UL/DL traffic variations.
- Ultra-lean design: NR embraces ultra-lean design that minimizes always-on transmissions. Take the design of NR reference signals as an example. The NR reference signals are on-demand when possible, and their time and frequency distributions are configurable so that requirements can be met with minimal overhead. In LTE, multiple functions are tied to the always-on cell-specific reference signals (CRS). In contrast, NR reference signal transmission can be extremely sparse at low load. The ultra-lean design leads to higher network energy efficiency and lower interference in 5G NR.
- Forward compatibility: The design of NR encompasses a high degree of forward compatibility that helps to facilitate the introduction of new technologies and applications. First, NR can configure reserved radio resources that are not available for transmission. Through reservation, resources are left blank and thus can be used for future extensions. Second, physical signals and channels are confined in configurable or scheduled radio resources. This yields flexibility for the future while being backward compatible. Third, NR minimizes always-on transmissions. It can be recognized that these forward compatibility designs align with the ultra-lean design principle. The high flexibility of the design and the on-demand principle result in a high degree of forward compatibility.
- Low-latency support: Latency optimization has been an important consideration in NR. Many tools have been introduced in NR to reduce latency. As an example, NR supports "mini-slot" transmission that can start at any OFDM symbol and last only as many symbols as needed for the communication. NR also supports front-loaded reference signals and control signaling that are located at the beginning of the transmission. This can help reduce decoding delay as a device can start to process the received data without buffering. Besides physical layer, certain optimization has also been introduced in higher layer protocols to support low latency.

- Advanced antenna technologies: NR significantly enhances the support of using a large number of antenna elements for both transmission and reception to facilitate beamforming in millimeter wave bands and deploying massive MIMO systems in sub-6 GHz frequency bands. An NR device can support spatial multiplexing of up to eight MIMO layers in the downlink and of up to four MIMO layers in the uplink. Multi-user MIMO capability is much enhanced with the introduction of twelve orthogonal demodulation reference signals (DMRS). NR supports analog beamforming, digital beamforming, or a hybrid combination of both, by carefully designing the physical channels, signals, and procedures. Beam management procedures including beam selection and beam-failure recovery are introduced in NR to support beamforming operations in millimeter wave bands. To facilitate devices to handle the increased phase noise power in millimeter wave bands, transmission of phase tracking reference signals (PTRS) is supported in NR.
- Coexistence with LTE: NR supports functionality to well coexist with LTE. For initial NR deployment, there is an option, known as non-standalone (NSA), that allows NR to focus on user plane functionality by utilizing existing LTE network for control plane functions. NR supports the possibility to have an NR carrier and an LTE carrier overlapping with each other in frequency, thereby enabling dynamic sharing of spectrum between NR and LTE. This facilitates a smooth migration to NR from LTE. Solutions specified to allow this type of operation are the ability for NR physical downlink shared channels to map around LTE CRS, and the possibility of flexible placements of downlink control channels, initial access related reference signals and data channels to minimize collisions with LTE reference signals. NR also supports a so-called supplementary uplink (SUL), which can be used as a low-band complement to the cell's uplink when operating in high frequency bands. A supplementary downlink (SDL), that can be used, for example, in downlink only spectrum, is also supported in NR.

Core Network

In addition to new radio access network, 3GPP has also developed a new 5G core network (5GC) in order to flexibly support a wide range of services with varied performance requirements in the 5G era. 5GC is responsible for functions such as end-to-end connection setup, mobility management, authentication, and charging. 5GC has a service-based architecture, focusing on the services rather than nodes [6]. 5GC features end-to-end flexibility by separating the software functions from the core network hardware. This network softwarization is achieved through software-defined networking (SDN), network functional virtualization (NFV), network slicing, and cloud-based radio access networks (C-RAN).

- SDN separates network control functions from network forwarding functions. Such separation enables network control to become directly programmable and abstracts the physical networking resources such as routers, switches, and gateways. Configuration and management of the physical networking resources can be moved to central data centers. Separating user plane functions from control plane functions is a distinct feature of 5GC. It allows independent scaling, evolution, and flexible deployments of the control plane and user plane, which facilitates the adoption of SDN.

- NFV virtualizes the entire networking functions including network forwarding from the hardware on which it runs. A virtualized network function can run on commercial off-the-shelf hardware, instead of having a custom hardware. With on-demand instantiation of network functions, NFV can facilitate load balancing, upgrades, and scaling and help to reduce the cost of network changes. 5GC has been designed to comprise virtualized, software-based network functions, which enables deployments to use NFV.
- Network slicing allows a shared physical network to be split into multiple virtual networks. A network slice is a dedicated virtual network that has self-contained functionality to support a certain type of service or customer. Network slicing is a key ingredient of 5G to serve the wide range of services with varied performance requirements. The allocated resources to a network slice depend on the service needs. For example, a network slice for eMBB needs to meet the high requirements for bandwidth, while a network slice for URLLC needs to meet the high reliability and low latency requirements. The modularized function design in 5GC can enable flexible and efficient network slicing.
- C-RAN is centralized, cloud computing-based architecture that features centralized processing units and virtualization techniques. Cloudification can facilitate network slice management to enable better support of the wide range of 5G services. Through enabling 5G deployments to use SDN and NFV, 5GC naturally supports cloudification and allows a virtualized network function to be instantiated on a cloud infrastructure.

Backhaul and Fronthaul

Backhaul connects the radio access network to the core network. Compared to the previous generations of mobile communications systems, 5G needs to deliver much higher data rates, lower latency, and greater capacity. Accordingly, 5G backhaul needs to be capable enough to accommodate the 5G technical requirements and should not become the bottleneck of the 5G systems. There are two types of backhaul: wired and wireless. Fiber is a prominent example of wired backhaul. Fiber optics can provide high capacity and high reliability for 5G backhaul. Though the fiber backhaul is often considered as a default option by many operators, its cost may be a concern in some scenarios, such as building the fiber backhaul in suburban and rural areas.

Wireless backhaul is an attractive viable alternative for 5G networks, especially in the scenarios where laying wired backhaul is too costly. Microwave backhaul may use a wide range of frequencies from about 6 to 86 GHz (and even higher frequencies that are under investigation). The range of frequencies enables the microwave backhaul to be used in diverse scenarios from rural areas to dense urban environments. Wireless backhaul may go beyond terrestrial. High-altitude platform systems (HAPS) and satellite technology may also play a role in 5G backhaul. They can complement terrestrial backhaul by offering backhauling to the areas that are difficult to be reached by terrestrial backhaul.

Fronthaul connects the remote radio units (RRU) of a base station to the centralized radio controllers. The logical architecture of 5G NodeB (gNB) is split into two parts called CU (central unit) and DU (distributed unit). The CU and DU are connected by a new interface called F1. The high data rates, low latency, and large capacity requirements of 5G require a fronthaul network to be capable of meeting the stringent demands. The more the centralized functions, the higher the requirements of fronthaul latency and bandwidth. The conventional common public radio interface (CPRI)-based fronthaul cannot meet the 5G technical requirements. The evolved CPRI (eCPRI) will improve the 5G fronthaul capabilities with lower latency and increased bandwidth efficiency and capacity. With eCPRI, it becomes possible to move the beamforming processing from the baseband to the radio, which can simplify the deployment of massive MIMO in 5G.

1.3.4 5G Spectrum

5G NR is designed to operate in a wide range of frequencies. Each spectrum band has its unique characteristics. NR can use new frequency bands defined for 5G, as well as the frequency bands refarmed from the spectrum used by the previous generations of mobile communications systems. To maximize the value of spectrum assets, a service provider should balance and combine the use of low-band, mid-band, and high-band spectrum to achieve quality performance.

- *Low-band* spectrum is below 1 GHz. Due to the desirable propagation properties, low-band spectrum is good for providing wide-area and deep indoor coverage. The channel bandwidths in low-band spectrum are however not wide (e.g., 20 MHz).
- *Mid-band* spectrum is in the range of 1–7 GHz. In mid-band spectrum, channel bandwidths of 50 to 100 MHz are possible. The wide bandwidths can enable networks of large capacity, high data rate, and low latency. Compared to high-band spectrum, mid-band spectrum has better wide-area and indoor coverage properties. Hence, the mid-band spectrum provides good compromise between coverage, capacity, data rate, and latency.
- *High-band* spectrum is in the millimeter wave frequencies above 24 GHz. In high-band spectrum, channel bandwidths up to 400 MHz are possible. The wide-spectrum bandwidths can provide very high data rate and ultra-large capacity. High bands are ideal for localized dense deployments to enable high-throughput and low-latency services. It is however difficult to provide wide-area coverage by using high-band spectrum alone due to the propagation characteristics in millimeter wave frequencies.

5G networks require significantly more spectrum resources to meet the demanding technical requirements. ITU-R identifies and coordinates IMT frequency bands for spectrum harmonization. A new set of frequency bands have been identified, such as the 600 MHz band and the 700 MHz band in the low-band spectrum, the 3.5 GHz band in the mid-band spectrum. ITU-R strives to define a minimum set of bands to facilitate global roaming for devices and economy of scale for equipment.

3GPP continuously defines new operating bands for NR, including both paired bands for FDD and unpaired bands for TDD. Note that there are also unpaired SDL and SUL bands, which are intended to be used together with other bands. In Release 15, frequency bands for NR are divided into two frequency ranges (FR):

- FR1: 410 MHz–7.125 GHz [7].
- FR2: 24.25 GHz–52.6 GHz, commonly referred to as millimeter wave [8].

NR operating bands are defined with prefix of "n" and are numbered from n1 to n512. The range of n1 to n256 is used for the NR bands in FR1, and the range of n257 to n512 is used for the NR bands in FR2. For example, band n71 is a paired band in the 600 MHz frequency for FDD with uplink frequency range of 663–698 MHz and downlink frequency range of 617–652 MHz; band n261 is an unpaired band in the 28 GHz frequency for TDD with uplink and downlink frequency ranges of 27.50–28.35 GHz. If an LTE band is refarmed as an NR band, they share the same band number. The full list of NR frequency bands can be found in 3GPP TS 38.101 [7, 8].

1.4 5G Standardization

Mobile communications standardization is based on consensus of all relevant parties. The history of mobile communications systems has proven that global standards are fundamental to the success of mobile technologies. A globally standardized mobile technology enables global roaming and ensures compatibility, worldwide interoperability, and quality, making the technology more affordable due to economies of scale. The standardization processes are however quite complex, involving standards developing organizations, global and regional regulatory bodies, national administrations, and industry forums.

When it comes to 5G standardization, ITU and 3GPP are the two essential organizations that define 5G. ITU is a specialized agency of the United Nations for information and communication technologies. The main roles of ITU in 5G include spectrum regulation on a global level and setting 5G requirements. 3GPP is a global standard-development organization for mobile communications. It has seven regional telecommunication associations from Asia, Europe, and North America as primary members.

The following two sections describe the main 5G standardization activities in ITU and 3GPP, respectively. Figure 1.3 gives a high level overview of the 5G standardization timeline.

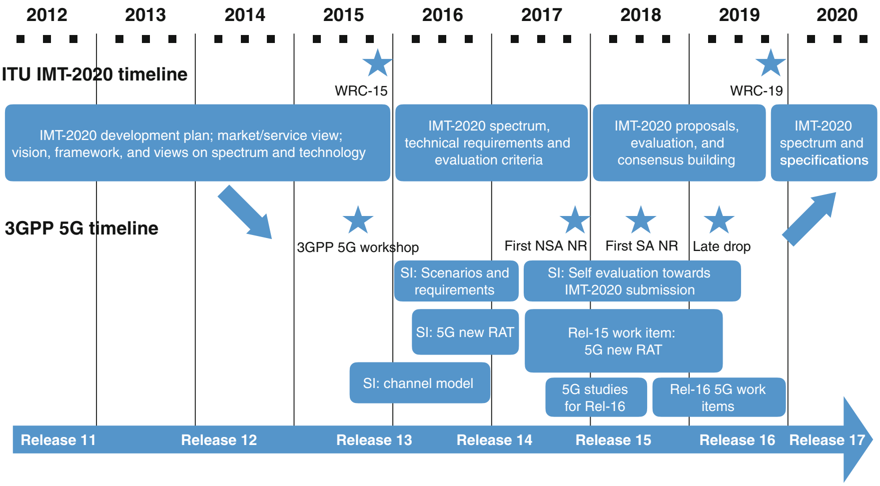

Fig. 1.3 5G standardization timeline

1.4.1 *ITU 5G Activities*

ITU comprises three sectors: radio communication sector (ITU-R), telecommunication standardization sector (ITU-T), and telecommunication development sector (ITU-D). ITU-R manages radio spectrum and satellite orbits. The mission of ITU-R is to ensure rational, equitable, efficient, and economical use of the radio spectrum by all radio communication services. A key activity of ITU-R is organizing the world radiocommunication conferences (WRC), which are held every 3 to 4 years. At WRC, the *Radio Regulations*, an international treaty that is binding to ITU member states, are reviewed and revised.

ITU-R approves *Recommendations* developed by ITU-R study groups. There are currently six study groups in ITU-R:

- Study group 1: Spectrum management.
- Study group 3: Radiowave propagation.
- Study group 4: Satellite services.
- Study group 5: Terrestrial services.
- Study group 6: Broadcasting services.
- Study group 7: Science services.

Within each study group, subgroups including working parties (WPs) and task groups (TGs) are established to carry out studies. Within the ITU-R study group 5, the working party 5D (WP 5D) is responsible for the overall radio system aspects of IMT systems. The term IMT is the root name that currently encompasses IMT-2000, IMT-Advanced, and IMT-2020, which correspond to 3G, 4G, and 5G mobile communications systems, respectively. WP 5D does not create technical specifications but maintains a set of radio interface specifications (RSPC). For each

IMT generation, there is a set of radio interface technologies (RITs). The RSPC contains overview of each RIT and references to the detailed specifications that are developed and maintained by the corresponding standards developing organizations.

In early 2012, ITU-R WP 5D started a program known as "IMT for 2020 and beyond." This set the stage for 5G research activities worldwide. The Recommendation ITU-R M.2083 [2] depicts the IMT vision on the framework and overall objectives of the future development of IMT for 2020 and beyond. The recommendation examines user and application trends, growth in IMT traffic (detailed in the Report ITU-R M.2370 [9]), technology trends (detailed in the Report ITU-R M.2320 [10]), technical feasibility of IMT between 6 and 100 GHz (detailed in the Report ITU-R M.2376 [11]), and spectrum implications. The recommendation emphasizes that IMT should continue to contribute to connecting the world, new market of information and communications technology, bridging the digital divide, new ways of communication, new forms of education, energy efficiency, social changes, and new art and culture. The recommendation describes diverse usage scenarios including eMBB, URLLC, and mMTC, envisaged for IMT for 2020 and beyond. To support the intended usage scenarios, the recommendation envisions a broad variety of capabilities of IMT-2020.

At WRC 2015 (WRC-15), spectrum for IMT was discussed. WRC-15 decided to make the 700 MHz band (694–790 MHz), a globally harmonized band for providing enhanced mobile broadband capacity. Frequency bands in the L-band (1427–1518 MHz) and in the lower part of the C-band (3.4–3.6 GHz) were also identified. Finding additional spectrum for IMT in the bands above 6 GHz is necessary due to the spectrum crunch in the sub-6 GHz frequency range. Accordingly, WRC-15 decided to have an agenda item (1.13) for the next WRC in 2019 to identify frequency bands in the frequency range between 24.25 and 86 GHz.

After WRC-15, WP 5D continued with spectrum arrangements, setting technical performance requirements, and defining evaluation criteria for IMT-2020. WP 5D published three reports in 2017:

- The Report ITU-R M.2410 [12] describes the minimum technical performance requirements of IMT-2020 candidate radio interface technologies.
- The Report ITU-R M.2411 [13] details the service, spectrum, and technical performance requirements for the IMT-2020 candidate radio interface technologies, as well as the evaluation criteria and submission templates for developing Recommendations and Reports on IMT-2020.
- The Report ITU-R M.2412 [14] elaborates the procedure, the methodology, and the criteria for evaluating the IMT-2020 candidate radio interface technologies.

WP 5D held a workshop on "IMT-2020 Terrestrial Radio Interfaces" in October 2017. The workshop provided information on the process for IMT-2020 standardization and presented potential IMT-2020 technology proponents. Independent evaluation groups also made presentations about their planned actions.

In 2018–2020, IMT-2020 technology proponents submitted their proposals and independent external evaluation groups carried out the evaluation.

WRC 2019 (WRC-19) took a big step in making high frequency millimeter wave spectrum available for 5G including the frequency bands 24.25–27.5 GHz, 37–43.5 GHz, 45.5–47 GHz, 47.2–48.2, and 66–71 GHz. In total, 17.25 GHz of spectrum was identified for IMT after the WRC-19.

The whole IMT-2020 process is planned to be completed in 2020. The key outcome will be the publication of a new ITU-R Recommendation with detailed specifications for the IMT-2020 radio interfaces.

1.4.2 3GPP 5G Standardization

3GPP writes technical specifications for mobile technologies. The standardization work is contribution-driven and consensus based. The project coordination group (PCG) coordinates the overall 3GPP work. The specification work is carried out in three technical specification groups (TSGs): TSG RAN (Radio Access Networks), TSG SA (Services and Systems Aspects), and TSG CT (Core Network and Terminals). The standardization process usually consists of four stages that are overlapping and iterative:

- In stage 1, the service requirements are defined.
- In stage 2, the architecture (including reference points and interfaces) for supporting the service requirements is defined.
- In stage 3, the detailed specifications of the protocols for the defined architecture are produced.
- In stage 4, test specifications are defined.

The 3GPP specifications are divided into releases. Each release consists of a set of features defined in agreed work items.

3GPP started to work on 5G, while ITU began to define IMT-2020. The 3GPP TSG RAN 5G workshop held in September 2015 marked the official start of 5G NR work in 3GPP. At this workshop, there was emerging consensus that a new, non-backward compatible radio access technology would be developed as part of 5G. It was emphasized at the workshop that the new radio access technology should embrace forward compatibility to ensure that the new radio would be capable of meeting new use cases in the future. It was also decided that the work would be split into two phases:

- Phase 1 would be completed by the second half of 2018 (i.e., end of 3GPP Release 15). It was highlighted that in this phase the focus should be on eMBB to facilitate early 5G deployments.
- Phase 2 would be completed by the end of 2019 (i.e., end of 3GPP Release 16) to address all identified use cases and requirements. This would pave the way for the 3GPP IMT-2020 submission to ITU-R.

At the 3GPP TSG RAN 5G workshop, a study item on channel modeling for frequencies up to 100 GHz was also approved. This study prepared channel models for the solution evaluations in developing the new radio access technology that would use new spectrum, particularly millimeter wave. The outcome of this study was documented in the 3GPP TR 38.900 [15] that details the channel models for frequencies from 6 GHz up to 100 GHz. Later, a new 3GPP TR 38.901 [16] was created to capture the channel models not only for frequencies from 6 GHz to 100 GHz but also for frequencies from 0.5 GHz to 6 GHz.

Following the 3GPP TSG RAN 5G workshop, a new study item focusing on developing scenarios and requirements for NR was approved at TSG RAN#70 in December 2015. The outcome of this study was documented in the 3GPP TR 38.913 [17] that details the scenarios, requirements, and key performance indicators for the next-generation access technologies.

The study item on new radio access technology was approved at TSG RAN#71 in March 2016. The scope of this study was to investigate the technology components to be considered for NR. The outcome of this study was documented in the 3GPP TR 38.912 [18] that covers all the RAN aspects of the technology components.

After the series of studies, 3GPP approved a work item at TSG RAN#75 in March 2017 for NR specifications as part of Release 15. At this RAN plenary meeting, 3GPP introduced NSA NR and agreed to accelerate the 5G NR schedule to complete the NSA NR by December 2017, while SA NR was set to be completed by June 2018 as originally scheduled. The reason for accelerating the 5G NR schedule was to enable early large-scale 5G trials and deployments. An intermediate milestone was reached in December 2017 with the approval of the NSA NR specifications. The SA version was completed in June 2018. The last step for Release 15 was a late drop that was completed in March 2019.

The finalization of the Release 15 NR specifications was a major milestone. The focus of NR in Release 15 was eMBB, while URLLC was addressed to some extent. The set of Release 15 specifications can fulfill a subset of the ITU 5G requirements. It is also the basis for further evolution of 5G NR. 3GPP continued NR evolution in Release 16 towards a more complete specifications that can completely fulfill all the ITU 5G requirements. Release 16 is the release that 3GPP uses for IMT-2020 submission. Key Release 16 work items include dual connectivity and carrier aggregation enhancements, URLLC enhancements, industrial IoT, vehicle-to-everything (V2X), MIMO enhancements, integrated access and backhaul, positioning, unlicensed operation, UE power saving, cross-link interference handling, and remote interference management. In addition, 3GPP initiated several studies to broaden the applicability of 5G NR, e.g., exploiting frequencies beyond 52.6 GHz and non-terrestrial radio access (primarily satellites).

During the 5G NR specification work, 3GPP also conducted a study on self-evaluation towards the IMT-2020 submission. The study covers evaluations for two 5G submissions: the first is a set of RITs containing NR and LTE, and the second is a separate RIT for NR only. The outcome of this study was documented in the 3GPP TR 37.910 [19] that includes evaluations against the technical performance requirements, spectrum requirements, and service requirements defined by ITU-R. The study concluded that both the set of RITs and the NR RIT can meet the IMT-2020 requirements.

1.5 What Will 6G Be?

As the 5G NR specification is maturing, research communities have recently started to look at the future of mobile communication systems, a.k.a. 6G systems. Although 6G is still at a premature stage, this section aims to provide an overview of the vision, challenges, and key enabling technologies for 6G. This overview shares common ideas in part with [20–22], yet provides some different angles for 6G.

1.5.1 Vision for 6G

What will 6G be? Arguably, 6G systems are expected to provide intelligent and personalized (or task-dependent) services to users at any time and in any place. Billions of wireless devices, including sensors and mobiles, will be placed in homes, cars, buildings, factories, cities, and any environments. These devices will frequently connect to the network whenever they need. This creates meaning information per requested task by interacting with (distributed) data centers, each with high computing capabilities. As a result, the upcoming 6G will make a paradigm shift by not just connecting all wireless devices but also providing optimized information timely for any specific requests of users in a given environment. Providing new intelligent connectivity services can be one vision of 6G.

1.5.2 Technical Requirements and Applications

The NR specification for 5G has already made a successful progress towards attaining very high data rates, ultra-high reliability and low latency, and massive connectivity solutions. To provide task-dependent intelligent services, however, 6G systems may need to meet more challenging requirements than 5G. These include (1) extremely high data rates, such as a few terabits per second; (2) super-low latency, less than hundreds of microseconds; and (3) ultra-massive connectivity providing more than 10^7 connections per square kilometer, which cannot be offered by the current 5G standard. The key breakthrough applications that will accelerate the development of such 6G might include duplicated digital twin, pervasive connectivity, and 3D holographic display, among others.

- Digital twin technology [23, 24]: The main idea of the duplicated digital twin is to build an exact digital replica of a complex physical object or system. By feeding a set of data obtained from the real object, this replica mimics the real object behaviors to learn how the real system can evolve under time-varying circumstances and predict the best action for the next to optimize the system. This intelligent control system has already existed. For instance, General Electric developed the digital twins of jet engine components, which are critical to controlling the life-time of the engine. This idea will be explored in many

complex systems such as 6G wireless networks, industrial IoT networks, and quantum computers to maximize their performance while providing up-to-date information for a given task request. The extremely high data rates of a few Tbps and super low latency less than several hundred microseconds might be key technical requirements in addition to the availability of cloud computing and the machine learning technologies to enable this application.
- Pervasive connectivity for automation: The number of IoT (or M2M) connections will approximately be 14.7 billons in 2023, according to Cisco Annual Internet Report announced in February 2020. In a particular urban area, a connectivity solution that offers more than 10^7 IoT device connections per square kilometer would be needed. Therefore, 6G networks are required to hold the capability to connect this massive number of sensors in homes, cars, factories, and cities in a seamless manner. This is a realization of pervasive connectivity or "connectivity everywhere." 6G will not just provide such ubiquitous connectivity but also offer intelligent automation services for an enormous variety of wireless devices, thanks to the convergence between communications and intelligent computing capabilities empowered by machine learning technologies. The super-low latency of less than several hundred microseconds will be the key requirement for wireless connection to enable this situational awareness automation services. The energy efficiency will also play a key role in solving scalability obstacles for massive connectivity.
- 3D holographic display [25, 26]: Future wireless devices such as smartphones, tablets, and laptops might have enhanced display systems. 3D holographic display is the most promising technology that can be embedded in future wireless devices. This next-generation display system will be a primary driving force to increase the peak data rates for 6G networks. For instance, the data rate of 4.32 Tbps would be required to send a raw hologram data without any advanced compression technologies [26]. The super-low latency requirement of less than several hundred microseconds will also be critical to synthesize and synchronize the hundreds of different 2D images when building a 3D image in real time.

1.5.3 Key Enabling Technologies

We present five disruptive technologies that can enable the upcoming 6G.

- **Terahertz communications:** An effective way of increasing the data rate by an order of magnitude more than 5G is the use of a larger signal bandwidth. This strategy was already taken in the evolution from 4G to 5G by adopting millimeter wave frequency bands. This trend will continue to the next-generation wireless systems, 6G, to increase data rates more than 5G. In March 2019, the FCC announced a new category of experimental spectrum licenses for frequencies between 95 GHz and 3 THz. This has propelled researchers to have eyes on sub-terahertz bands, specifically in the range of 140 GHz and 300 GHz [27]. The use of THz frequency bands for wireless transmissions will be a critical enabler to provide extremely high-speed data rates for 6G.

Communications using THz frequency bands is very challenging. The signal bandwidth is ultra-wide, and the propagation is highly directional. In addition, the compound channel effects, including blockage and molecular absorption, are not fully understood yet. Pencil beams will also provide two sides of the same coin in managing interference, which will affect medium access control and handover. Terahertz communications will impose another challenge in physical-layer designs. The challenges will include the development of modulation, coding, and beamforming techniques under impairments of RF hardware, low-power AD/DA conversion circuits constraints, and antenna mutual coupling effects.

Obtaining spatial multiplexing gains is also not trivial in sub-terahertz line-of-sight (LOS) MIMO communications. Unlike conventional MIMO channels under 6 GHz frequency bands, in which rich scattering is pronounced, fixed-link LOS MIMO channels in sub-terahertz bands are completely determined by physical parameters such as link distances, antenna array geometries, and wavelengths. Orbital angular momentum (OAM) multiplexing technologies can be suitable for short-range MIMO communications using sub-terahertz bands [28]. The use of reconfigurable uniform linear arrays as a function of system parameters is also a promising technique for sub-terahertz LOS MIMO communications, which was recently proven to be optimal from an information-theoretical viewpoint. This technique can achieve the maximum spectral efficiency under all possible antenna configurations in LOS MIMO channels [29].

- **Pilot-free communications:** Short packet transmissions are essential to enable extremely low-latency communications. By shrinking the packet size, it is possible to dwindle not only air-interface time but also the computation time for decoding; thereby, it possibly enables to meet the stringent delay requirement of less than a hundred microseconds for 6G. The challenge in pilot-based short packet communications is that longer pilots make larger transmission delays. The pilot length can also linearly increase with the number of connected wireless devices to support the massive connectivity. Furthermore, when a channel coherence time is very short in the scenarios such as V2X, the pilot-based communication is not very effective, because the pilots are repeatedly transmitted whenever channel realizations change. Lastly, the pilot-free uplink communications make it possible to eliminate the pilot contamination effects in TDD massive MIMO systems. In theory, this has the potential to achieve an infinite cellular capacity when the number of base station antennas is infinite. Therefore, pilot-free communication technologies will be key enablers for supporting delay-sensitive massive IoT/V2X communications and massive MIMO systems for 6G.

  The pilot free communications will bring a fundamental challenge in reliable message decoding due to the absence of channel knowledge. Several non-coherent communication methods have been developed such as differential modulation and a geometric approach based on the Grassmann manifold [30].

These techniques may not be suitable to meet the stringent requirements of ultra-high reliability and low latency. Joint modulation and coding techniques using compressive sensing and machine learning-aided blind detection technologies are envisaged to enable pilot-free communications for 6G.

- **Convergence of communication, sensing, and computing:** The convergence of communications, sensing, and computing technologies will play an essential role in 6G. Future wireless devices such as self-driving cars and next-generation smartphones are likely to have multi-functionalities offered by communication transceivers, radar, and many sensors. Radar systems measure the reflections of probing signals to detect the presence of objects. In addition, vision sensors can acquire environmental landscapes and scenery surrounding users or cars. They, therefore, provide users with information on complex environments with different angels. Leveraging mobile edge computing technologies with the power of machine learning, this environmental information can be processed to generate user-specific contextual data. This contextual data will contain the multidimensional information of users such as users' activity (e.g., mobile contents) pattern and space-time map of users' geographical information. This multifaceted information can be exploited to predict future behaviors of users to improve the quality of services, which enables context-aware communication systems.
- **Communications using quantum computation:** The availability of quantum computation can bring a breakthrough in the design of communication algorithms. The quantum computation differs from quantum communications that exploit the quantum physical phenomenon called quantum entanglement to transfer information in one place to another. Instead, it uses quantum entanglement to speed up the computation in solving a class of NP-hard optimization problems. The quantum community has recently shown that the exponential speedups in computation is possible for a certain class of NP-hard optimization problems. In this area, the main research challenge is to develop both low-cost quantum processors and advanced algorithms that take advantages of quantum processors. For example, D-Wave is a quantum processor that enables quantum annealing, which is a metaheuristic approach to finding a global optimal solution using the phenomena of quantum fluctuations [31]. The quantum approximate optimization algorithm (QAOA) is another promising quantum-classical hybrid technique that solves combinatorial optimization problems using gate-based noisy quantum devices (e.g., IBM quantum computers) [32]. Harnessing these quantum optimization techniques, one may solve the long-standing computationally challenging optimization problems in communications, including maximum likelihood (ML) detection in massive MIMO, ML decoding of channel codes, and the capacity-maximizing resource allocation algorithms. This new computation capability can propel to improve the data rates and delay performance significantly for 6G.
- **Flexible 4D cellular networks:** Mobile base stations mounted on moving objects such as unmanned aerial vehicles (UAVs), drones, and smart cars can provide an additional degree of freedom in designing a 4D cellular network

[33]. This new degree of freedom can offer a high flexibility that adaptively changes infrastructure configurations in both space and time to optimize network performance. This will be a key feature of 6G cellular networks. By flying the UAV base stations in a densely populated area, one can optimize the network performance by offloading effects. The moving base stations can also provide cellular operators with flexible and scalable space-time coverage maps by eliminating the coverage limitations of the existing cellular networks. When the cellular infrastructures break down due to disastrous events, they are capable of creating wireless connectivity in a cost-effective manner. For example, people may use satellite networks for communications by using UAV base stations as mobile relays/routers under disastrous environments. The mobile base stations will offer new opportunities to provide user-specific contents while guaranteeing high quality of service requirements.

Several critical problems remain open to enable the flexible cellular networks in space-time. Wireless backhaul solutions that can provide ultra-high throughput would be essential. The flying base stations, for example, may use millimeter wave or sub-terahertz LOS MIMO transmission technologies to achieve data rates of a few Tbps. Innovative battery technologies for UAVs and drones are needed for lasting flying base station missions. In addition, low-power mobile edge computing technologies supporting advanced machine learning algorithms will be another essential part of realizing the mobile cellular base stations.

1.6 Book Outline

This book provides an accessible but complete tutorial on the key enabling technologies for 5G and beyond covering both the fundamentals and the state-of-the-art of the 5G standards.

The rest of this book consists of three parts.

- **Part I – Fundamentals of 5G and 6G**: The first part describes the fundamental technology components for 5G and beyond.
  - Chapter 2 presents an accessible treatment of advanced channel coding theory with a focus on rate-compatible polar codes that are capacity-achieving.
  - Chapter 3 provides a comprehensive overview of the state-of-the-art multiple access techniques and discusses rate-splitting multiple access in detail.
  - Chapter 4 gives a tutorial on massive MIMO including a massive MIMO transmission protocol, fundamental aspects, and future research directions.
  - Chapter 5 focuses on network densification and introduces theoretical models based on stochastic geometry for densified network analysis and design.
  - Chapter 6 discusses the integration of unmanned aerial vehicles in cellular communication networks.
  - Chapter 7 presents a comprehensive forward-looking vision that defines the main principles that will guide the design and development of a 6G system.

- **Part II – 5G New Radio Basics**: The second part introduces the basics of 5G NR standards.
    - Chapter 8 offers a guide to the new generation 5G radio access network (NG-RAN) architecture that provides both NR and LTE radio access.
    - Chapter 9 outlines the NR physical layer highlighting aspects around waveforms and numerologies, bandwidth parts, downlink and uplink control information, downlink and uplink data channels, NR-LTE interworking on the physical layer, power control, and UE capabilities.
    - Chapter 10 provides an accessible description of 5G NR channel coding design aspects. It includes both polar codes for control channels and LDPC codes for data channels
    - Chapter 11 describes cell search and random access procedures in 5G NR.
    - Chapter 12 presents a primer on the bandwidth parts concept in 5G NR, delving into more details beyond the short introduction in Chapter 9.
- **Part III – 5G New Radio Evolution**: The third part describes key 5G NR evolution directions.
    - Chapter 13 provides an overview of NR URLLC by describing the use cases, performance requirements, and standards enhancements.
    - Chapter 14 introduces 5G NR operation in unlicensed spectrum including targeted spectrum and requirements, deployments, and design details.
    - Chapter 15 gives a tutorial on NR positioning. It discusses location services in 5G, fundamentals of positioning, and NR positioning methods and reference signals.
    - Chapter 16 provides an overview of NR integrated access and backhaul (IAB) system architecture, key issues, and designs.
    - Chapter 17 describes how NR can be used for air-to-ground (A2G) communications and discusses potential NR evolution directions for enhanced NR based A2G systems.
    - Chapter 18 discusses how to adapt the NR air interface for non-terrestrial networks with a focus on satellite communications.

Acknowledgement N. Lee is supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1C1C1013381).

References

1. Ericsson, Ericsson Mobility Report November 2019, Tech. Rep., Nov 2019. [Online]. Available: https://www.ericsson.com/4acd7e/assets/local/mobility-report/documents/2019/emr-november-2019.pdf
2. ITU-R, IMT vision–framework and overall objectives of the future development of IMT for 2020 and beyond, Recommendation ITU-R M.2083, Sept 2015

3. X. Lin, J. Li, R. Baldemair, T. Cheng, S. Parkvall, D. Larsson, H. Koorapaty, M. Frenne, S. Falahati, A. Grövlen et al., 5G new radio: unveiling the essentials of the next generation wireless access technology. IEEE Commun. Stand. Mag., **3**(3), 30–37 (2019)
4. J.G. Andrews, S. Buzzi, W. Choi, S.V. Hanly, A. Lozano, A.C. Soong, J.C. Zhang, What will 5G be? IEEE J. Sel. Areas Commun. **32**(6), 1065–1082 (2014)
5. X. Lin, Debunking seven myths about 5G new radio, arXiv preprint arXiv:1908.06152, Aug 2019
6. 3GPP, System architecture for the 5G system (5GS), 3GPP TS 23.501, V16.1.0, June 2019
7. 3GPP, NR; user equipment (UE) radio transmission and reception; Part 1: range 1 standalone, 3GPP TS 38.101-1, V16.0.0, July 2019
8. 3GPP, NR; user equipment (UE) radio transmission and reception; Part 2: range 2 standalone, 3GPP TS 38.101-2, V16.0.0, July 2019
9. ITU-R, IMT traffic estimates for the years 2020 to 2030, Report ITU-R M.2370-0, July 2015
10. ITU-R, Future technology trends of terrestrial IMT systems, Report ITU-R M.2320-0, Nov 2014
11. ITU-R, Technical feasibility of IMT in bands above 6 GHz, Report ITU-R M.2376-0, July 2015
12. ITU-R, Minimum requirements related to technical performance for IMT-2020 radio interface(s), Report ITU-R M.2410-0, Nov 2017
13. ITU-R, Requirements, evaluation criteria and submission templates for the development of IMT-2020, Report ITU-R M.2411-0, Nov 2017
14. ITU-R, Guidelines for evaluation of radio interface technologies for IMT-2020, Report ITU-R M.2412-0, Oct 2017
15. 3GPP, Study on channel model for frequency spectrum above 6 GHz, 3GPP TR 38.900, V15.0.0, June 2018
16. 3GPP, Study on channel model for frequencies from 0.5 to 100 GHz, 3GPP TR 38.901, V15.0.0, June 2018
17. 3GPP, Study on scenarios and requirements for next generation access technologies, 3GPP TR 38.913, V15.0.0, July 2018
18. 3GPP, Study on new radio (NR) access technology, 3GPP TR 38.912, V15.0.0, July 2018
19. 3GPP, Study on self evaluation towards IMT-2020 submission, 3GPP TR 37.910, V16.0.0, June 2019
20. Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G.K. Karagiannidis, P. Fan, 6G wireless networks: vision, requirements, architecture, and key technologies. IEEE Veh. Technol. Mag. **14**(3), 28–41 (2019)
21. W. Saad, M. Bennis, M. Chen, A vision of 6G wireless systems: applications, trends, technologies, and open research problems. IEEE Netw. **34**(3), 134–142 (2020)
22. E. Calvanese Strinati, S. Barbarossa, J.L. Gonzalez-Jimenez, D. Ktenas, N. Cassiau, L. Maret, C. Dehos, 6G: the next frontier: from holographic messaging to artificial intelligence using subterahertz and visible light communication. IEEE Veh. Technol. Mag. **14**(3), pp. 42–50 (2019)
23. N. Mohammadi, J.E. Taylor, Smart city digital twins, in *2017 IEEE Symposium Series on Computational Intelligence (SSCI)*, Nov 2017, pp. 1–5
24. Z.F.A. Fuller, C. Day, Digital twin: enabling technology, challenges and open research, arXiv preprint arXiv:1911.01276, 2019
25. J. Park, K. Lee, Y. Park, Ultrathin wide-angle large-area digital 3D holographic display using a non-periodic photon sieve. Nat. Commun. 10, 1304 (2019). https://doi.org/10.1038/s41467-019-09126-9
26. X. Xu, Y. Pan, P.P.M.Y. Lwin, X. Liang, 3D holographic display and its data transmission requirement, in *2011 International Conference on Information Photonics and Optical Communications*, Oct 2011, pp. 1–4
27. Y. Xing, T.S. Rappaport, Propagation measurement system and approach at 140 GHz-moving to 6G and above 100 GHz, in *2018 IEEE Global Communications Conference (GLOBECOM)*, Dec 2018, pp. 1–6

28. J. Wang, J.-Y. Yang, I.M. Fazal, N. Ahmed, Y. Yan, H. Huang, Y. Ren, Y. Yue, S. Dolinar, M. Tur, A.E. Willner, Terabit free-space data transmission employing orbital angular momentum multiplexing. Nat. Photonics **6**, 488–496 (2012)
29. H. Do, N. Lee, A. Lozano, Reconfigurable ULAs for line-of-sight MIMO transmission. arXiv preprint arXiv:2004.12039, April (2020)
30. L. Zheng, D.N.C. Tse, Communication on the grassmann manifold: a geometric approach to the noncoherent multiple-antenna channel. IEEE Trans. Inf. Theory **48**(2), 359–383 (2002)
31. C.S.A. Finnila, M. Gomez, J. Doll, Quantum annealing: a new method for minimizing multidimensional functions. Chem Phys. Lett. **5–6**, 343–348 (1994)
32. J.G.E. Farhi, S. Gutmann, A quantum approximate optimization algorithm, arXiv, 2014
33. C. Yan, L. Fu, J. Zhang, J. Wang, A comprehensive survey on UAV communication channel modeling. IEEE Access **7**, 107769–107792 (2019)