CHAPTER

INTRODUCTION: 5G RADIO ACCESS 1

Information and communication technologies (ICT) have sparked innovations in almost every society. The ever-growing capabilities for instantly transferring and processing information are transforming our societies in many ways—online shopping, social interactions, professional networking, media distribution, e-learning, instant information access, remotely watching live events, audio and video communication, virtual offices and workforce, and so on. Various industries and corporations have also been evolving their processes and businesses based on technological advancements in information and communication technologies.

Fifth generation (5G) mobile communication is expected to enormously expand the capabilities of mobile networks. New technologies and functionalities are being introduced for 5G systems in various domains—wireless access, transport, cloud, application, and management systems [6]. These advancements are targeting traditional mobile broadband users as well as emerging machine-type users, so that new and superior services can be enabled for both consumers and industries at large, unleashing the potential of the internet of things (IoT), and virtual and augmented reality. According to a recent survey performed across 10 different industries [4], the global revenues driven by 5G technologies will be as high as 1.3 trillion USD by 2026 (see Fig. 1.1 for revenues per industrial segment). It is estimated that by 2023, there will be around 3.5 billion cellular IoT connections [24].

The backbone of any mobile communication system is its wireless access technology, which connects devices with radio base stations. As almost every society and industry is looking forward to the 5G revolution with its specific set of requirements, the design of the 5G wireless access is challenging. A 5G wireless access technology is expected to provide extreme data rates, ubiquitous coverage, ultra-reliability, very low latency, high energy efficiency, and a massive number of heterogeneous connections. The human-centric emerging applications are augmented reality, virtual reality, and online gaming—these demand extreme throughput and low latency. For machine-type communication there are two main segments: massive IoT and critical IoT. Massive IoT is characterized by a high number of low cost device connections, supporting small volumes of data per device with long battery life and deep coverage (for example, for underground and remote areas). The applications are in smart buildings, utilities, transport logistics, agriculture, and fleet management. The critical IoT is characterized by ultra-reliability and very low-latency connectivity, for example, to support autonomous vehicles, smart power grids, robotic surgery, traffic safety, and industrial control.

This book is about the upcoming 5G wireless access technology, and it focuses on its physical layer. A preview of the book is provided in Section 1.4. This chapter gives a holistic view of the 5G wireless access technology and its global development. We start with a brief history of mobile access technologies in Section 1.1 and introduce the 5G mobile access technology in Section 1.2. In Section 1.3, we provide a global picture of 5G wireless access—spectrum allocations, standardization, use cases and their requirements, field trials, and future commercial deployments.

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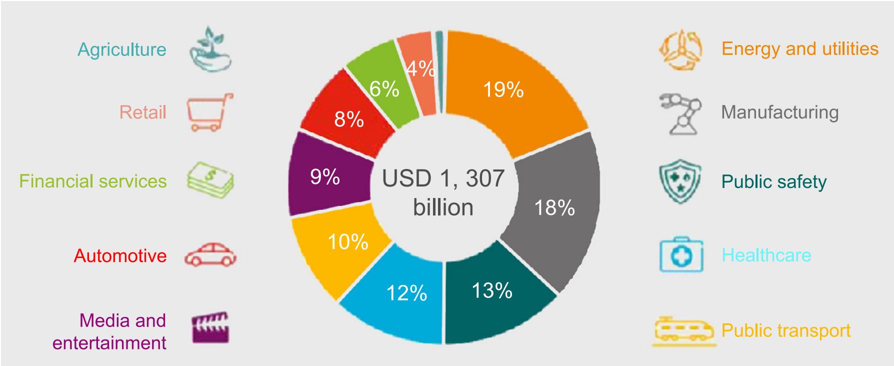

FIGURE 1.1

5G enabled industry digitalization revenues for ICT players, 2026 (Source: Ericsson [4]).

1.1 EVOLUTION OF MOBILE COMMUNICATION

In 1946, the US federal communications commission (FCC) approved a first mobile telephony service to be operated by AT&T in 1947. At this time, the equipment were bulky and had to be installed in a vehicle due to the weight and its excessive power consumption. From this point on, more than three decades of cellular communication technology evolution has led to a shift from analog to digital formats of communication, going from what was mainly voice to high-speed data communication.

Leading up from the mid-1980s, the first generation (1G) of cellular communication, which mainly carried voice, grew up using formats such as advanced mobile phone system (AMPS) in the USA and nordic mobile telephone (NMT) in Scandinavia. These analog formats were later replaced moving towards 2G with the first digital communication schemes around the mid to late-1990s—global system for mobile communications (GSM) in Europe and digital-AMPS for the USA. At this point, the short message service (SMS) was introduced, being one of the first widely used non-voice applications for cellular communication. Enhancement for 2.5G using enhanced data rates for GSM evolution (EDGE), general packet radio service (GPRS) and code division multiple access (CDMA) sparked the use of mobile data communication and early cellular internet connectivity in the early-2000s. This was an early enabler, which did, however, require a specific protocol, known as wireless application protocol (WAP).

Moving forward from 2G into 3G, in order to meet the increasing demand for cellular access data rates, universal mobile telecommunications system (UMTS) based on wideband CDMA (WCDMA) technology was introduced by third generation partnership project (3GPP) just around 2000. With advances in mobile user equipment technology, this enabled the user to not only communicate via multimedia message service (MMS), but also stream video content. Transitioning to 4G, long term evolution (LTE) was introduced, which does not only imply major changes on the air interface, but was moving from code division multiplexing to orthogonal frequency division multiplexing (OFDM) and time division duplex (TDD) or frequency division duplex (FDD).

Entering the era of 4G, there were mainly two competing technologies at an early stage. These were worldwide inter-operability for microwave access (WiMAX), based on IEEE 802.16m, and LTE Advanced, which is an extension of LTE. LTE-A introduced technology components such as carrier aggregation and improved support for coordinated multipoint (CoMP) transmission and heterogeneous network (HetNet) deployments for improving Quality of Service (QoS) in hot-spots and coverage for cell-edge users. LTE-A prevailed as the dominant cellular access technology today and has served as the basis of the transition to 5G mobile communications. The transition from 4G to 5G is inspired by new human-centric and machine-centric services across multiple industries.

1.2 5G NEW RADIO ACCESS TECHNOLOGY

5G wireless access is envisioned to enable a networked society, where information can be accessed and shared anywhere and anytime, by anyone and anything [2]. 5G shall provide wireless connectivity for anything that can benefit from being connected. To enable a truly networked society, there are three major challenges:

- A massive growth in the number of connected devices.
- A massive growth in traffic volume.
- A wide range of applications with diverse requirements and characteristics.

To address these challenges, 5G wireless access not only requires new functionalities but also substantially more spectrum and wider frequency bands.

Fig. 1.2 illustrates the operational frequency ranges of existing (2G, 3G, 4G) and future (5G) mobile communication systems. The current cellular systems operate below 6 GHz. A large amount of spectrum is available in the millimeter-wave frequency band (30–300 GHz); however, there is no commercial mobile communication system operating in the millimeter-wave frequencies today. 4G LTE is designed only for frequencies below 6 GHz. There are some local area networks and (mostly) indoor communication systems based on the IEEE 802.11ad and 802.15.3c standards that operate in the unlicensed 60 GHz band. IEEE 802.11ay, a follow-up of 802.11ad, is under development. 3GPP is currently developing a global standard for new radio access technology, 5G new radio (NR), which will operate in frequencies from below 1 GHz up to 100 GHz. 5G NR shall unleash new frequencies and new functionalities to support ever-growing human-centric and machine-centric applications.

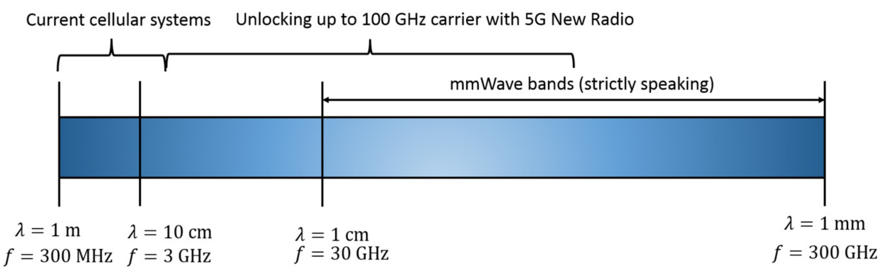

FIGURE 1.2

Frequency ranges of current and future mobile communication systems.

The vision of 5G wireless access is shown in Fig. 1.3. 5G wireless access comprises both 5G NR and LTE evolution. LTE is continuously evolving to meet a growing part of the 5G requirements. The evolution of LTE towards 5G is referred to as the LTE Evolution [13]. LTE will operate below 6 GHz and NR will operate from sub-1 GHz up to 100 GHz. 5G NR is optimized for superior performance; it is not backwards compatible to LTE, meaning that the legacy LTE devices do not need to be able to access the 5G NR carrier. However, a tight integration of NR and LTE evolution will be required to efficiently aggregate NR and LTE traffic.

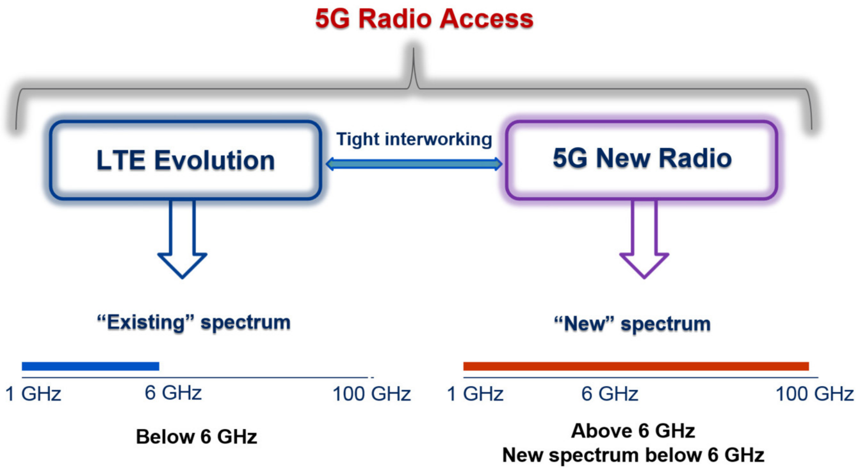

FIGURE 1.3

5G radio access vision.

1.3 5G NR GLOBAL VIEW

The research and concept development of the 5G wireless access technology (named 5G NR since 2016) started almost a decade ago with new inspiring applications and business cases in mind. The research efforts led to development of 5G test-beds in universities as well as industry. Like previous generations of cellular systems, the development of 5G NR is a well-coordinated global effort—addressing the new spectrum allocations on global and regional levels for 5G NR and the global 5G NR standardization in 3GPP based on the 5G requirements defined by international telecommunications union (ITU). To give a global picture of the 5G NR developments, we will in the following discuss spectrum allocations and regulatory aspects, the standardization process, major use cases and their requirements, some precommercial trials, and expected commercial deployments.

1.3.1 5G STANDARDIZATION

The specifications for NR and LTE are developed by the 3GPP which is a collaboration between seven regional and national standard development organizations from Asia, Europe and North America:

ARIB, ATIS, CCSA, ETSI, TSDSI, TTA, and TTC. 3GPP produces technical specifications which are transposed into standards by the standardization bodies. 3GPP was started in 1998 with the initial goal of developing globally applicable specifications for the third generation (3G) of mobile communications. The scope has since then been widened and now includes the development and maintenance of specifications for the second generation (2G) GSM, 3G WCDMA/HSPA, fourth generation (4G) LTE, and 5G NR/LTE evolution.

The international radio frequency (RF) spectrum is managed by the ITU-radiocommunications sector (ITU-R). ITU-R has also a responsibility to turn technical specifications from, e.g., 3GPP into global standards, including also countries not covered by the standardization bodies in 3GPP. ITU-R also defines the spectrum for the so-called international mobile telecommunications (IMT) systems. The IMT systems correspond in practice to the different generations of mobile communications, from 3G onwards. The 3G and 4G technologies are included in the IMT-2000 and IMT-Advanced recommendations, respectively. A new ITU-R recommendation for 5G, called IMT-2020, is planned to be developed in 2019–20.

ITU-R does not produce the detailed technical specifications but defines IMT in cooperation with regional standardization bodies by specifying requirements that an IMT technology should fulfill. The actual technology is developed by others, e.g. 3GPP, and submitted to ITU-R as a candidate IMT technology. The technology is evaluated against the specified requirements and may then be approved as an IMT technology. ITU-R gives recommendations of radio interface technologies in radio interface specifications for a particular IMT system and provides references to the corresponding detailed specifications which are maintained by the corresponding standardization bodies. The IMT-2000 radio interface specifications include six different radio interface technologies while IMT-Advanced includes two. Unlike previous generations, for 5G it is not expected that competing technologies will be submitted as candidates for IMT-2020; only 3GPP-based technologies are anticipated. 3GPP will submit LTE evolution and NR together as their candidate system for IMT-2020.

Different generations of mobile communications have appeared around every ten years. However, the individual systems are continuously evolving with new features. The 3GPP specifications are divided into releases, where each release consists of a complete and self-contained set of specifications. This means that a particular release contains all components needed to build a complete cellular network, not just the newly added features. When a release is completed, the features are frozen and ready for implementation. When a release has been frozen, only essential corrections are permitted. Further functionalities will have to go into the next release. The work on different releases has some overlap, so that the work on a new release starts before the completion of the current release. The releases should be backwards compatible so that a user equipment (UE) developed for one release can also work in a cell that has implemented a previous release. The first version of LTE was part of release 8 of the 3GPP specifications. LTE release 10 was named *LTE-Advanced* since it was approved as an IMT-Advanced technology by ITU-R. In release 13, the marketing name for LTE changed to *LTE-Advanced Pro*.

The everyday 3GPP work is divided into study items and work items. Study items are feasibility studies of concepts, where the results are documented in a technical report (TR). The details of agreed concepts are worked out in the work items, where the features are defined and end up in a technical specification (TS). The 3GPP technical specifications (TSs) are organized in series and are numbered TS XX.YYY, where XX defines the series. The radio aspects of NR are defined in the 38-series. All 3GPP specifications are publicly available at www.3gpp.org.

Organizationally, 3GPP consists of three technical specification groups (TSGs) where TSG radio access network (RAN) is responsible for the radio access specifications. TSG RAN in turn consists of six working groups (WGs), where RAN WG1 deals with the physical layer specifications. The WGs meet regularly and come together four times a year in TSG plenary meetings. The decisions in 3GPP are based on consensus among the members.

Fig. 1.4 illustrates the ITU and 3GPP time lines as well as the expected development of commercial equipment for 5G. The standardization work of 5G NR started in 3GPP in April 2016, with the aim of making it commercially available before 2020. 3GPP is taking a phased approach in defining the 5G specifications. A first standardization phase, with limited NR functionality, NR release 15, was completed for non-stand-alone (NSA) operation at the end of 2017 and for stand-alone (SA) operation in mid-2018. The second standardization phase, NR release 16, is expected to meet all the requirements of IMT-2020 and be completed by 2019.

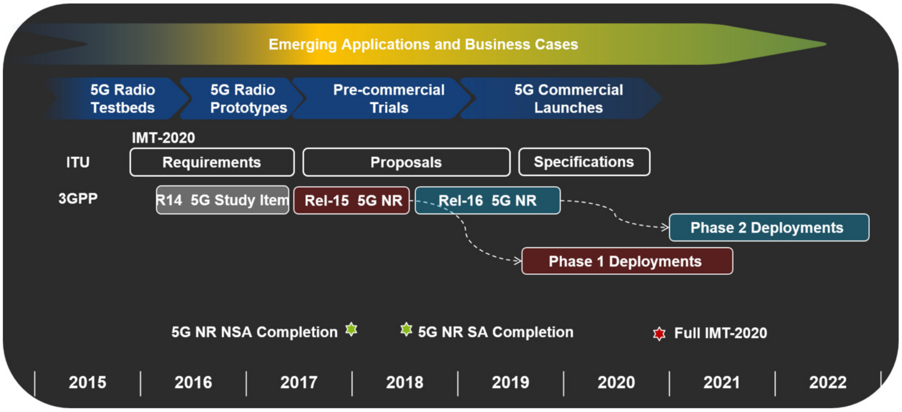

FIGURE 1.4

5G global view.

With 5G standardization in acceleration, 5G precommercial trials are also taking place worldwide. Based on the release 15 specifications, 3GPP-compliant base stations and devices are already under development. The commercial deployments are then expected in two phases. The first phase of NR commercial deployments is expected in 2019; it is based on the release 15 specifications. The second phase of NR commercial deployments is expected to start in the 2021 time frame, based on the release 16 specifications. It is likely that the NR specifications will continue to evolve in 3GPP beyond 2020, with a sequence of releases including additional features and functionalities.

1.3.2 SPECTRUM FOR 5G

One of the main changes when going from previous generations of mobile communications to the fifth generation is the spectrum use at radically higher frequencies in the millimeter-wave range. 3GPP has decided to support the range from below 1 GHz up to 52.6 GHz already from the first releases of NR [12]. A main reason for this change is the availability of large amounts of spectrum with very large

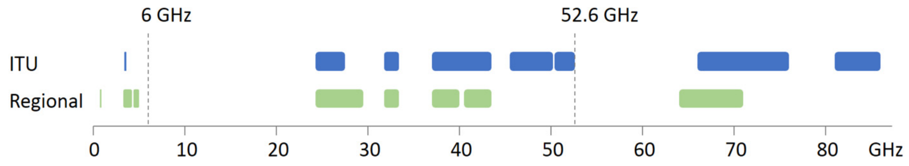

FIGURE 1.5

Global (ITU) and regional spectrum identifications for 5G.

bandwidths in the range of several GHz. Though the millimeter-wave spectrum seems very attractive, there are also many challenges:

- The transmission loss goes up substantially if multiantenna and beam-forming techniques are not used.
- RF hardware performance regarding e.g. phase noise and output power is degraded.
- There is no non-utilized spectrum, meaning that coexistence, with e.g. satellite systems, will be required where acceptable interference levels have to be guaranteed.

As a consequence, 5G is designed by 3GPP (NR) for flexible frequency use over the full frequency range. Joint operation at lower frequencies and higher frequencies is supported in order to provide both reliable coverage (utilizing e.g. frequencies below 6 GHz) and very high capacity and bitrates when possible (where millimeter-wave coverage is available).

An overview of the spectrum identified for 5G is given in Fig. 1.5. The 3300–3600 MHz band was identified as a global IMT band by ITU-R at world radiocommunication conference (WRC)-15.[1] The corresponding global allocation above 6 GHz is subject for WRC-19. There is a substantial additional regional spectrum identified below 6 GHz. Above 6 GHz the regional spectrum is largely overlapping with the global bands except for around 28 GHz and 65 GHz. It is evident that the amount of spectrum below 6 GHz is scarce and that spectrum above 6 GHz will be needed for fulfilling the requirements of 5G. For early deployments of 5G, bands below 6 GHz at 600–700 MHz, 3300–4200 MHz, and 4400–5000 MHz have drawn attention [11]. Except the 3300–3600 MHz band which was identified as a global IMT band at WRC15 these bands are subject to regional regulations.

In Europe the focus for early deployments is put on the 3600–3800 MHz band [3]. Also the United States, Japan, South Korea and China use different allocations in the 3300–4200 MHz band in their planning for early 5G systems, and 3GPP is developing a specification for this band.

The 4400–5000 MHz band is mainly promoted by China and Japan but could potentially also be adopted by other countries in the Asia–Pacific region.

Though the bandwidth is limited in the 600–700 MHz band, it is useful for providing coverage as the transmission losses are low without requiring any advanced multiantenna transmission techniques. There are already allocations for LTE at 700 MHz which could be migrated to 5G in 2020 or later. Moreover, the United States has identified 614–698 MHz for mobile use.

In the process of allocation of IMT frequencies above 6 GHz it was decided at WRC-15 to study 11 bands in the range 24.5 GHz to 86 GHz for decisions at WRC-19. ITU-R has estimated the maximum

[1] A WRC is held every 3–4 years where regulations are revised for the RF spectrum use across the world.

need of spectrum for 5G to be up to 20 GHz [8]. As the current situation is that most spectrum is already allocated, this amount of spectrum can hardly be allocated for IMT primary use, and coexistence will be required. For this reason, a crucial part of the spectrum studies prior to WRC-19 is to assess whether the different bands are suitable with respect to coexistence with incumbent systems, such as satellites.

The interference between IMT and other systems on earth, in air or in space, is mainly of long range. For this reason, mainly the aggregation of multiple IMT transmitters is of interest. In this case the specific pointing directions and antenna gain is averaged out, providing an effective omni-directional radiation. For base stations, however, the radiation in elevation angle is focused in down-tilted directions.

In order to accurately determine interference signals between IMT and other systems, proper propagation models are required. Such models are provided by the ITU-R study group 3 recommendations. There are earlier recommendations (P.619, P.2041, P.1409, P.452, P.2001, etc.) which are valid for atmospheric propagation paths and paths over the earth profile and for the full range of frequencies under consideration by WRC-19. However, two important cases have been missing for modeling of additional losses due to clutter (vegetation and man made structures like buildings) and penetration into buildings. In March 2017 ITU-R study group 3 succeeded in providing proper models for these cases [10], [9]. The corresponding urban clutter loss is up to 50 dB (median) for low elevation angles. For higher elevation angles the clutter loss may be very low, down to 0 dB, as no buildings obstruct the sky. However, for these cases the building penetration loss for indoor transmitters is in the range 40 dB to 60 dB (median) at 30 GHz. As 5G deployments are expected to be highly concentrated in urban environments below roof-top and indoors, the urban clutter and building penetrations losses greatly improve the prospects for IMT coexistence with incumbent systems.

In addition to the global ITU process there have been a lot of regional efforts for finding a suitable spectrum for 5G. The United States, Korea, Canada, Japan, Singapore, and Sweden are focusing on bands in the 26.5–29.5 GHz range. The United States is also targeting bands in the 37–40 GHz range and Canada is considering the very high end of frequencies in the 64–71 GHz band. Both Europe and China have identified bands in the range 24.25–27.5 GHz. In addition China is looking at 37–42.5 GHz, whereas Europe considers the ranges 31.8–33.4 GHz and 40.5–43.5 GHz. The 5G spectrum availability around the world is summarized in Fig. 1.6.

Except the obvious need for contiguous bands of large bandwidths, the allocation of spectrum for 5G will crucially depend on the frequency dependent performance of RF hardware, propagation channel and multiantenna techniques. All these aspects are addressed in depth in Chapter 3, Chapter 4, and Chapter 7.

1.3.3 USE CASES FOR 5G

Differently from its predecessors, 5G has the goal of providing optimized support for a number of drastically different types of services and user requirements. Conforming to the ITU nomenclature for international mobile communications for 2020 and beyond (IMT-2020) [7], 5G will target three use case families with very distinct features: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable low-latency communications (URLLC). We will next describe the features of these three use case categories, which are depicted in Fig. 1.7

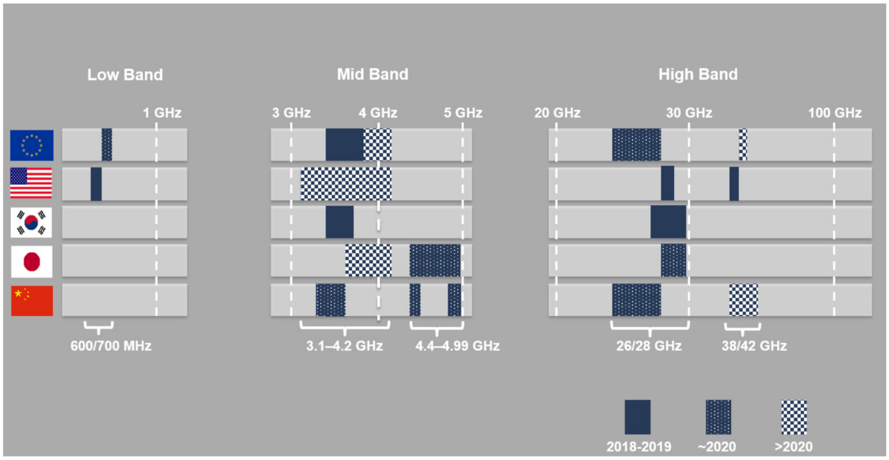

FIGURE 1.6

5G spectrum availability around the world.

eMBB:

This use case category is the natural extension of the classic mobile broadband connectivity scenario under current mobile telecommunication standards. It addresses human-centric connectivity, including access to multimedia content, services, and data. This is done by providing the high data rates that are required to support future multimedia services and the increasing traffic volume generated by these services. The eMBB use case covers a range of scenarios including:

- *Hotspot connectivity*, which is characterized by a high user density and extremely high data rates, and low mobility.
- *Wide-area coverage*, where the user density and data rates are lower, but the mobility is higher.

URLLC:

Stringent requirements on both latency and reliability are the distinctive features of this use case category, which targets mainly machine-type communications (MTC). Envisaged applications include wireless control of industrial manufacturing and production processes, remote medical surgery, driverless and/or remotely driven vehicles, and distribution automation in smart grids.

mMTC:

The growth of the Internet of Things (IoT) is causing a proliferation of wirelessly connected devices carrying MTC traffic. Indeed, the number of such devices is expected to exceed soon the number of devices carrying human-generated traffic. The focus of the mMTC is on providing connectivity to a massive number of devices, which are assumed to transmit sporadically a low amount of traffic, which is not delay critical. The mMTC devices are expected to have a very long battery lifetime to allow for remote deployments. A unique feature of this use case is that the MTC devices will be extremely heterogeneous in terms of capabilities, cost, energy consumption, and transmission power.

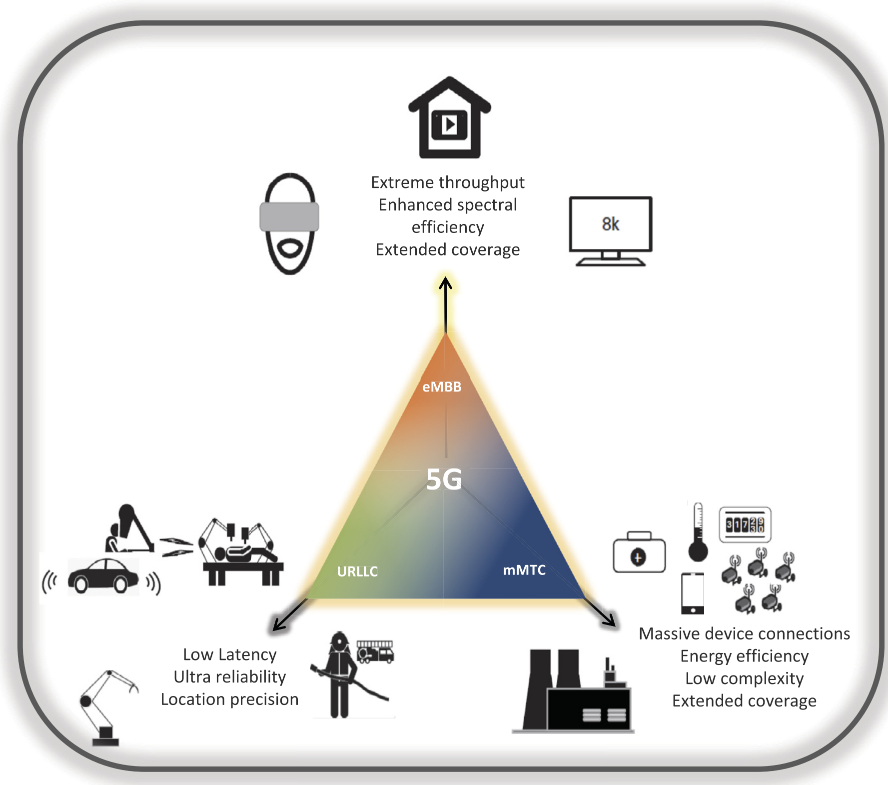

FIGURE 1.7

The three 5G use cases, according to the ITU nomenclature, and their main features.

Fig. 1.8 provides a graphical summary of some of the applications targeted by 5G, and their relation to the IMT-2020 use cases just reviewed.

The ITU has set key performance requirements for IMT-2020 to be able to address satisfactorily the specific needs of eMBB, URLLC, and mMTC traffic. Such requirements are summarized in Fig. 1.9, where a comparison with the key capabilities of the previous mobile generation—IMT-advanced—is provided. The requirements include a peak data rate of 20 Gbit/s, a latency below 1 ms, and the capability to support a connection density of 10^6 devices per square kilometer. As exemplified in Tables 1.1–1.2, NR is being designed to satisfy (in some cases, with large margins) all these requirements [1].

1.3.4 5G FIELD TRIALS

In the following, we will briefly present some of the world's most exciting 5G trials, which show the potential of 5G to unlock new and exciting opportunities. Some pictures from these trials are shown in Fig. 1.10.

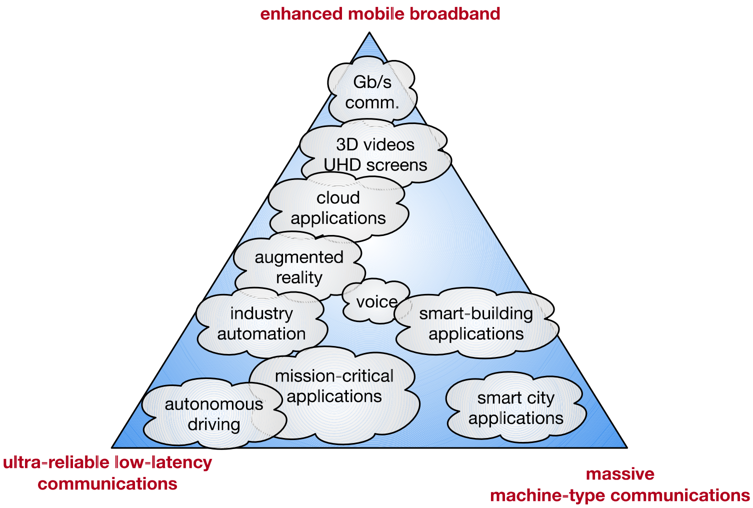

FIGURE 1.8

The three IMT-2020 use cases and some targeted applications.

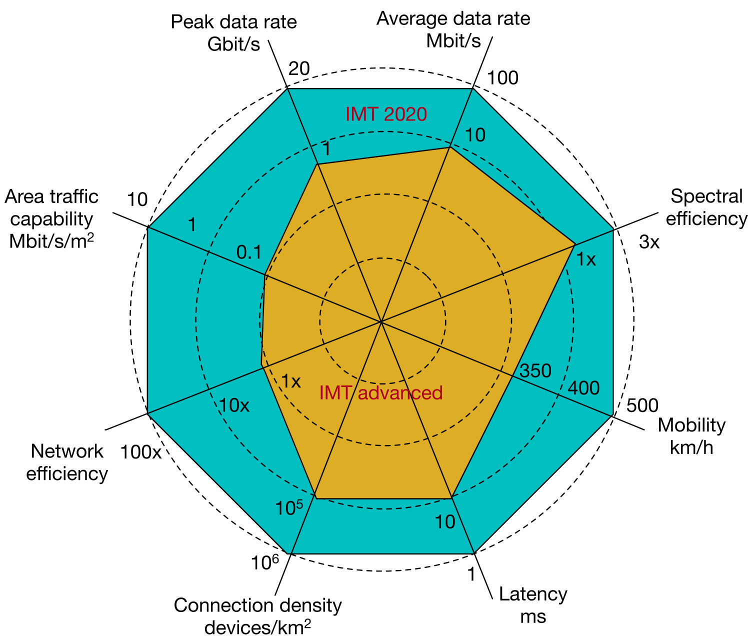

FIGURE 1.9

The key capabilities of IMT-2020 in relation to the ones of its predecessor, IMT-advanced.

Table 1.1 A subset of the performance requirements for high-data-rate and high-traffic-density scenarios. The complete list can be found in [1, Table 7.1-1]

Scenario	Data-rate DL	Data-rate UL	User density	Mobility
Urban macro	50 Mbit/s	25 Mbit/s	10^5 UEs per km^2	Up to 120 km/h
Indoor hotspot	1 Gbit/s	500 Mbit/s	25×10^4 per km^2	Pedestrian
High-speed train	50 Mbit/s	25 Mbit/s	10^3 per train	Up to 400 km/h

Table 1.2 A subset of the performance requirements for low-latency and high-reliability scenarios. The complete list can be found in [1, Table 7.2.2-1]

Scenario	Latency	Error probability	Data rate	Connection density
Motion control	1 ms	10^{-6}	Up to 10 Mbit/s	10^5 UEs per km^2
Transport system infrastructure backhaul	10 ms	10^{-6}	10 Mbit/s	10^3 UEs per km^2
Electricity distribution	25 ms	10^{-3}	10 Mbit/s	10^3 UEs per km^2

5G for flying drones: Ericsson and China Mobile successfully performed the world's first 5G trial for flying drones on a commercial network in 2016, with 5G enabled technologies on a cellular network [14]. A drone (an unmanned aerial vehicle) was flown with handovers across multiple sites. In order to demonstrate the concept's validity in a real-world setting, the handovers were performed between sites that were simultaneously in use by commercial mobile phone users. The applications of drones are emerging, for example, in agriculture, public safety, search and rescue, inventory management, and goods delivery.

5G connectivity for high-speed cars: Ericsson and Verizon tested the limits of 5G by demonstrating 6+ Gbps throughput and super-low latency inside a moving car in 2017 [20]. The car was completely backed out and the driver operated the car while wearing a set of virtual reality glasses, relying solely on video captured from a camera on the hood of the car. The trial showcased the massive potential of multiantenna technologies with beams tracking a high-speed car. This shows that 5G is capable of supporting 360-degree 4K video streaming with very low latencies, even in high mobility scenarios. This would, for example, give us the possibility to watch live sporting events with virtual reality.

A similar trial was also conducted by Ericsson, SK Telecom and BMW Group on a racetrack in Yeonjong-do, South Korea [22]. The test network consisted of four radio transmission points from Ericsson operating in the 28 GHz band at BMW Group Korea's driving center. Under this setup, test results achieved driving speeds of 170 km/h, while reaching downlink data speeds of 3.6 Gbps. This was enabled by advanced beam-forming and beam tracking, which allows the base station to transmit signals that follow the UEs.

5G connecting ships and ports: Tallink, Telia, Ericsson, and Intel have created a 5G test and exploration area at the Port of Tallinn in Estonia. Ericsson has set up a 5G base station in the port of Tallinn and Intel has placed equipment inside the ferries to receive signals. The 5G trial network is delivering high-speed internet connectivity to the commercial passenger cruise ships and their passengers while in the port area since 2017 [19].

5G delivering tens of Gbps worldwide: In 2016, Ericsson and Korea Telecom (KT) demonstrated the world's first 5G achieving 25.3 Gbps throughput [16]. The trial was performed in millimeter-wave frequency bands for 5G mobile communications. (KT was aiming to provide 5G trial services for the

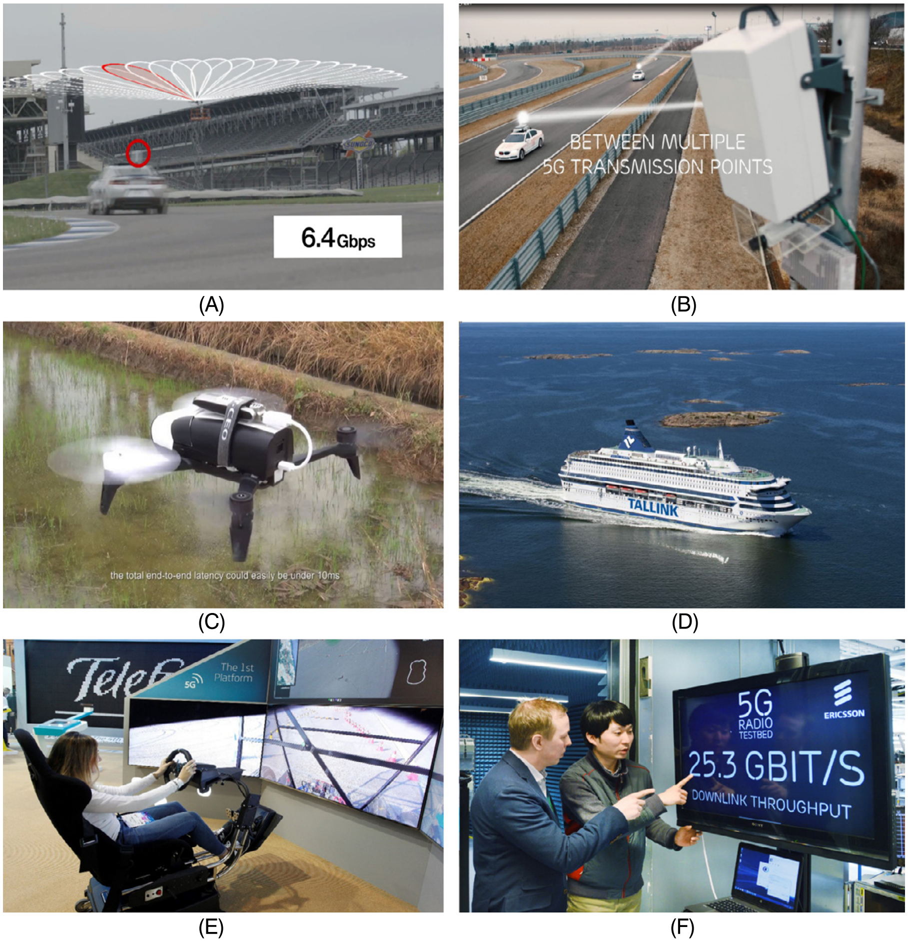

FIGURE 1.10

5G trials. (A) 5G connectivity for high-speed cars (Ericsson, Verizon); (B) 5G connectivity for high-speed cars (Ericsson, SK Telecom); (C) 5G for flying drones (Ericsson, China Mobile); (D) 5G connecting ships and ports (Ericsson, Telia, Tallink Grupp, Intel); (E) 5G for remotely driving cars (Ericsson, Telefonica); (F) 5G delivering tens of Gbps (Ericsson, Korea Telecom).

PyeongChang 2018 winter games.) In the same year (2016), Ericsson and Telstra conducted Australia's first live 5G trial, achieving 20+ Gbps and a latency of half of what is seen in Telstra's 4G networks [15]. The trial used 800 MHz of spectrum, which is 10 times more than what Telstra currently uses for its 4G networks.

Ericsson and Mobile Telesystems (MTS) have built a prototype 5G network in Moscow and successfully achieved 25 Gbps in 2017, with the use of advanced antenna systems on 5G base stations [21].

In January 2018, Mobile Telephony Network Group (MTN) and Ericsson performed the first 5G trial in Africa and achieved a throughput of more than 20 Gbps with less than 5-ms latency. This was the best performance ever achieved on a mobile network in Africa. The 5G trial was based on Ericsson's 5G prototype radios [23].

5G making remote driving a reality: Telefonica, Ericsson, the Royal Institute of Technology (KTH), and Applus Idiada developed a revolutionary demo to showcase the world's first 5G remote driving of a car on Applus Idiada race track during the Mobile World Congress 2017 [17,18]. A 5G base station provided connectivity to a car at 15 GHz carrier frequency. The driver in a remote location gets an in-car experience with 4K video streaming in the uplink. In the downlink, the 5G connectivity provides ultra-low latency and high reliability to communicate driving decisions to the car. One possible application of remote driving is remote parking, where a driver can leave a car in a drop-off zone and request assistance from a remote driver to ensure safe and efficient parking.

1.3.5 5G COMMERCIAL DEPLOYMENTS

The deployment of a 5G NR network should start from an existing 4G LTE network, which already has good coverage [5]. As shown in Fig. 1.3, NR can coexist and interwork with LTE, which reduces the time to market for NR. Commercial deployment of the 5G NR network is expected to occur in two phases:

1. The first phase is a non-standalone (NSA) mode, with tight interworking between 5G NR and LTE, as shown in Fig. 1.3. This option uses LTE as the control-plane[2] anchor for NR, and it uses either LTE or NR for user traffic (user-plane). The first 5G specification (3GPP Release 15, NSA) was finalized at the end of 2017. Fully standard-compliant radio systems are likely to be available at the end of 2018. We expect to see 5G NR to start being deployed during 2019.
2. The second phase is a standalone (SA) mode, with both control-plane and user-plane existing over 5G NR. The 5G specification for the SA mode was released in mid-2018. The commercial deployments for the SA mode are expected beyond 2020.

NR will need to coexist and interwork with LTE for many years to come, not only as a way of reducing the time to market but also ensuring good coverage and mobility. With 5G NR deployments, new use cases will pick up and 5G devices will come to market. We see the deployment of standalone NR beginning when devices are more widely available, new use cases (e.g., ultra-reliable and low-latency communications, industrial IoT) start to gain momentum, and NR has greater access to both new and existing spectrum. Ultimately, 5G NR is likely to become the mainstream cellular technology used to address multiple use cases across multiple industries. The evolution path of 5G NR deployments is sketched in Fig. 1.11.

There are three main 5G deployment scenarios considering that LTE operates below 6 GHz (i.e., low or mid frequency band) and NR can operate up to 100 GHz (i.e., in low, mid, and high bands) [5]:

1. **NR NSA in mid/low with LTE in low/mid band** In this deployment scenario, NR and LTE will have similar coverage per base station, since they are both deployed in similar frequencies. The

[2]The control-plane is mainly responsible for control signaling for connection setup, mobility (handovers), and security.

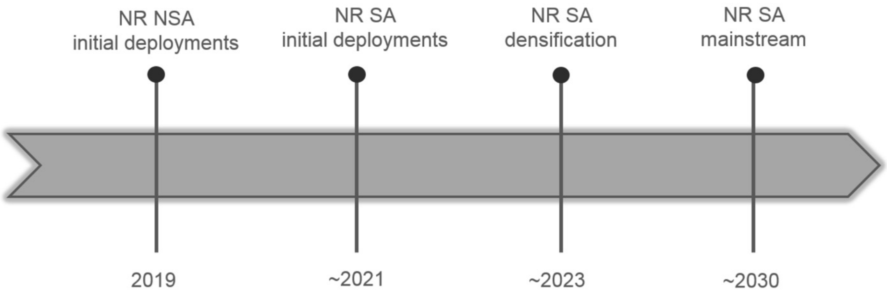

FIGURE 1.11

The evolution path of 5G NR deployments.

greater capacity and throughput enabled by the 5G NR spectrum implies that this is a more likely way to deployment for high user density areas, typically in city and urban areas.

2. **NR NSA in high band with LTE in low/mid band** In this deployment scenario, NR coverage area per base station will be smaller than LTE coverage area, due to higher transmission losses at higher frequencies. The main driver for this deployment is to enable high capacity and extreme throughput cells with wider channel bandwidths available in millimeter-wave frequencies. In addition to eMBB, fixed wireless access is an emerging use case for this deployment category.
3. **NR SA in mid/low/high band** NR standalone will be deployed in all frequency bands, depending on the spectrum availability. In addition to eMBB, standalone NR deployments are very likely to be used for private or enterprise networks to support industrial applications (for example, manufacturing). Although NR SA deployments do not rely on LTE for its operation, many NR SA deployments are likely to reuse the existing 4G physical infrastructure and transport network, thereby reducing the cost of deployment. NR NSA in low/mid bands will be suitable for massive IoT applications. Deployment of 5G NR in low bands is of interest to boost coverage. Deployments in high bands are more likely to be used for high-traffic areas and for private (industrial) IoT networks.

Although deployment for cost-efficient and well-performing 5G NR networks is crucial for 5G success, it is the availability of NR capable devices and their market uptake that will eventually determine growth driven by 5G NR connectivity. Fig. 1.12 shows approximate timing of NR capable devices. Early fixed wireless access devices are already available in some regions (e.g., in USA) for operation in high bands. The first 3GPP-compliant 5G smart-phones and tablets are likely to be launched in 2019. New NR capable devices for IoT are expected to be introduced in 2020 and beyond. For many IoT use cases, the cost of NR capable devices might have to significantly go down below eMBB devices in order to allow mass adoption. However, for critical IoT applications requiring high-reliability and very low-latency connections, device cost is not expected to be a barrier.

The United States will be among the first to experience 5G commercial services [24]. The major operators in the US have already announced that they will start providing 5G services between late 2018 and mid-2019. South Korea, Japan, and China are expected to be among early 5G service providers with significant volumes of 5G subscriptions. Ericsson forecasts over 1 billion 5G mobile broadband subscriptions by the end of 2023, accounting for 12 percent of all mobile subscriptions.

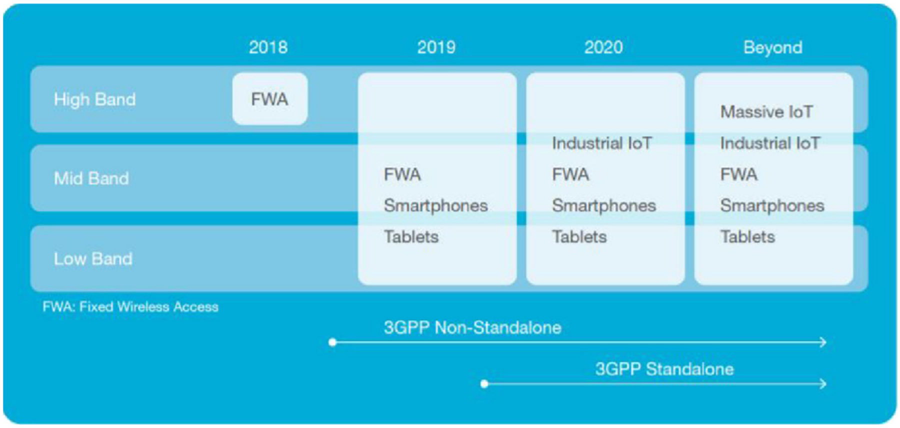

FIGURE 1.12

5G device availability (Source: Ericsson [5]).

1.4 PREVIEW OF THE BOOK

This book is written for researchers and system designers in the field of mobile radio communication, interested in understanding principles, models, and technology components for the 5G NR physical layer. Although the focus is on 5G NR, many concepts presented in the book are of a fundamental nature and are applicable beyond 5G. We assume that the reader has a basic understanding of digital wireless communications and signal processing; however, familiarity with cellular technologies (for example, 4G LTE standard) is not required. We will introduce relevant standard related concepts and terminologies in the book.

A preview of the book is sketched in Fig. 1.13, highlighting key aspects covered in various chapters. The book is composed of nine chapters covering various aspects of 5G NR—a global picture of its development, the physical layer overview based on the first 5G NR release in 3GPP, the physical limitations imposed by radio wave propagation and hardware impairments, the key physical layer technologies, and an open-source link-level simulator. In the following, we briefly outline the content of each chapter.

Chapter 1 introduces 5G NR and discusses global efforts in the development of 5G NR and its future impact on industry and society. We provide a holistic view on 5G use cases and their requirements, spectrum allocations, standardization, field trials, and future commercial deployments.

Chapter 2 provides an overview of the 5G NR physical layer based on the first 3GPP NR release. We will see that the physical layer components of NR are flexible, ultra-lean and forward-compatible. Moreover, we provide an overview of radio wave propagation and hardware impairment related challenges associated with enabling a high performing NR.

Chapter 3 presents state-of-the-art insights on radio wave propagation along with description of fundamental concepts and propagation characteristics. We focus on the frequency dependency of the channel properties for the full range of frequencies envisioned for 5G NR, with experimental examples.

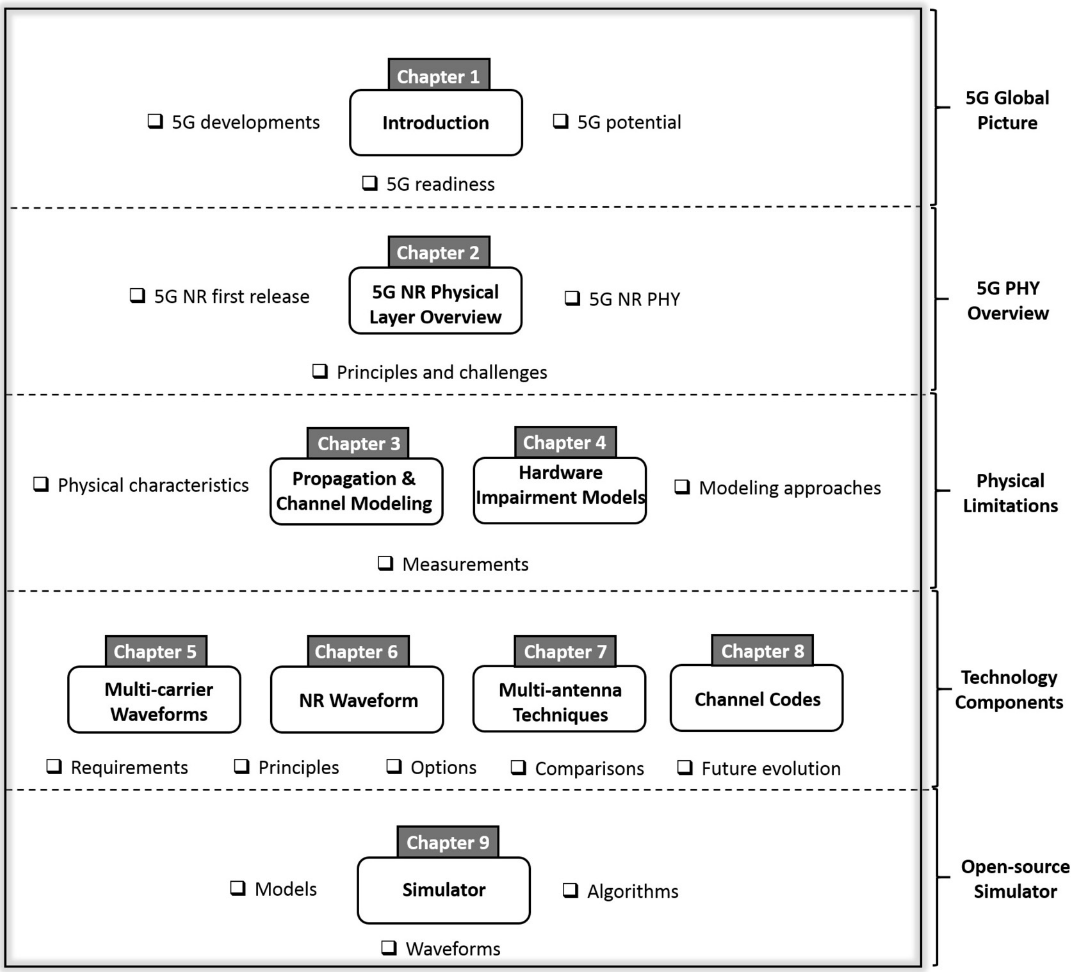

FIGURE 1.13

Preview of the book.

The channel modeling for 5G NR is discussed. Moreover, we point out both validated and non-validated (or deficient) aspects of the current 5G channel models defined by 3GPP and ITU-R.

Chapter 4 covers some of the traditional behavioral models for power amplifiers, local oscillators and data converters. These models may accurately predict the input–output relation of analog and mixed-signal components. Furthermore, a novel modeling approach is presented that provides the second order statistics of the errors caused by non-ideal components. This stochastic modeling framework provides a powerful tool for link-level evaluations and aids in making sound choices in terms of the radio performance versus energy efficiency trade-offs.

Chapter 5 presents state-of-the art multicarrier waveforms. Based on the design requirements for NR, the chapter provides an overall waveform comparison that has led to the down selection of CP-OFDM waveform for 5G NR. The multicarrier waveforms are compared as regards a number of key performance indicators: phase-noise robustness, baseband complexity, frequency localization, time localization, robustness to power amplifier nonlinearities, channel time selectivity and channel frequency selectivity.

Chapter 6 presents a flexible OFDM for 5G NR. Different factors involved in the implementation of OFDM-based NR modems are discussed, for example, quality of service requirements, type of deployment, carrier frequency, user mobility, hardware impairments, and implementation aspects. This chapter puts special focus on high carrier frequencies (e.g., millimeter-wave band), where robustness to hardware impairments (phase noise, synchronization errors) and power efficiency of the waveform is crucial.

Chapter 7 discusses the role of multiantenna techniques in 5G NR and the features included in the first release of the NR specifications. To provide an understanding and motivation of the features adopted by NR, the fundamental theory behind these features is provided. The viability of the multiantenna techniques presented is illustrated by several experimental examples.

Chapter 8 presents different channel coding schemes for 5G NR. The performance of the coding schemes is evaluated for different blocklength values. We review recently developed information-theoretic tools to benchmark the performance of these coding schemes. Looking beyond what is currently standardized in NR, we consider transmissions over multiantenna fading channels and highlight the importance of exploiting frequency and spatial diversity through the use of space-frequency codes, in applications that require high reliability.

Chapter 9 presents an open-source simulator that includes hardware impairment models (power amplifier, oscillator phase noise), a geometry-based stochastic channel model, and modulation/demodulation modules of state-of-the art waveforms. The chapter provides simulation exercises with various waveforms subject to different types of impairments.

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