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Standards History of Cellular Systems Toward 6G

In the summer of 1895, a few decades after the invention of the wire telephone, Guglielmo Marconi successfully demonstrated the feasibility of radio transmission. Since then, a wide variety of radio communications and broadcasting services were adopted throughout the world. Around half of a century later, the world-renowned research institution, Bell Labs, accomplished two historic innovations in the same year of 1947 – the Transistor and the Cellular concept. In the early 1980s, with tens of years' technical development, the first-generation cellular networks were finally rolled out to offer commercial mobile telephony service to the public. With its ease of deployment, economic efficiency, portability, flexibility, and scalability compared with wire-line networks, mobile cellular networks experienced explosive growth in the last decades. It became one of the critical infrastructures to empower modern society and drastically reshaped human behaviors in business, education, entertainment, and personal life. Recently, the term *5G* has been remained as one of the hottest buzzwords in the media, attracting unprecedented attention from the public. The whole society has got a consensus that the fifth-generation (5G) cellular system is one of the greatest innovations in the 2020s and will bring tremendous economic and societal benefits. At the moment of starting the writing of this book, more than 400 mobile operators in approximately 130 countries are deploying 5G networks, and the number of 5G subscribers in either the consumer market or vertical industries has already reached an enormous scale in many regions. Now, the attention of academia and industry is increasingly shifting toward the next generation. Since the first experiments with radio communications in the 1890s, it was quite a long journey to reach cutting-edge mobile communications. To well understand the complex cellular systems of today, it is vital to have a complete view of how cellular systems have evolved. To this end, the motivation of the first chapter in association with the following chapter is to provide the readers a brief review of the whole history of mobile cellular systems, from pre-cellular to the

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fifth generation. Then, the readers should be able to well prepared for getting insights into the forthcoming six-generation (6G) system. This chapter will be organized chronologically in terms of the generations. Each section dedicates to one generation of cellular systems, where the main content generally consists of three main parts:

- The underlying motivation of evolution.
- The milestones of development, standardization, and deployment.
- The review of various competing standards with their major technical features.

1.1 0G: Pre-Cellular Systems

Wireless communications had been exploited already in early ancient times when people tried to transfer critical messages such as the invasion of enemies by means of smoke, torches, flashing mirrors, signal flares, or semaphore flags. Long-range transmission was realized through the signal relaying over a network of observation stations built on beacon towers or mountain peaks. These infant communication systems were replaced by the electric telegraph (invented by Samuel Morse in 1837) that transferred text messages over landlines, and later the wire telephone (invented by Alexander Graham Bell in 1876), carrying information-rich voice signals. In the summer of 1895, a few decades after the invention of the telephone, Guglielmo Marconi successfully carried out the first experiment to illustrate the ability of radio communications. Since then, a wide variety of radio services such as wireless telegraph, mobile telephony, radio broadcasting, television broadcasting, satellite communications, wireless local area networks, and Bluetooth were adopted worldwide and sharply reshaped modern society. As the most successful form of radio technologies, mobile communications have experienced explosive growth in the last decades. Nowadays, cellular networks serve as the critical infrastructure and the basis for the mobile Internet that is an industry worth trillions of dollars per year.

The first cellular system originated in a portable radiophone known as Walkie-Talkie during World War II, symbolized by SCR-536 developed by Motorola for the US military. This handheld radio transceiver operated in a push-to-talk manner, allowing one radio to transmit while others in its range to listen (i.e. the half-duplex operation). It was primitive but gained much experience for the later development of pre-cellular mobile telephone systems. One of the earliest mobile telephone systems was known as Mobile Telephone Service (MTS), which was connected to the public telephone network as an extension of the wire telephone service and operated commercially in the United States in 1946 by Motorola in conjunction with the Bell System. On 17 June 1946, the Bell System demonstrated the world's first mobile call in the City of St. Louis through a car phone weighed around 36 kg. Initially, only 3 channels were available for all the subscribers in the metropolitan area but increased to 32 channels later. Within three years, this service had been expanded to 100 cities across the United States, attracting a total of 5 000 users. In 1964, an enhanced system named Improved Mobile Telephone Service (IMTS) was rolled out to replace the previous MTS system. It achieved two major advances: direct dialing allowing a phone call without manual connection by a human operator, and the full-duplex transmission, by which two communicating parties can talk simultaneously.

Such pre-cellular systems were the forerunners of the first generation of cellular networks, sometimes referred to as the zeroth generation (0G). These initial systems utilized a central transmission station to serve an entire metropolitan area. An IMTS base station generally covered a wide area with a diameter of 60–100 kilometers (km) using a transmit power of 100 Watts (100 W), in comparison with less than 1 W on modern base stations. Each voice conversation exclusively occupied a radio channel, but even a large cite was licensed with only a few channels, leading to very limited system capacity. In the 1970s, before the deployment of cellular networks, a customer wishing to subscribe to mobile telephone service had to wait for up to three years until an incumbent subscriber terminated his or her mobile subscription.

Cellular Network

The constraint of network capacity was the main driver for a more elegant network design known as the cellular system.

In 1947, William R. Young, an engineer who worked at AT&T Bell Labs, reported his idea about the hexagonal layout throughout each city so that every mobile telephone can connect to at least one cell. Douglas H. Ring, also at Bell Labs, expanded on Young's concept. He sketched out the basic design for a standard cellular network and published the intellectual groundwork as a technical memorandum entitled *Mobile Telephony – Wide Area Coverage* on Bell Labs' internal journal on 11 December 1947 [Ring, 1947]. In a cellular network, a wide area can be divided into small geographical areas called cells, each covered by a radio station. It allowed efficient reuse of precious spectral resources at spatially separated sites taking advantage of the fact that the power of a transmitted signal decays dramatically with distance.

Nevertheless, the development process of the cellular system from an initial concept to a practical network was quite a long journey due to technological barriers. AT&T requested a spectrum license for cellular service from the US Federal Communications Commission (FCC) as early as 1947, and the system design had been mostly completed in the 1960s. The first trial network consisting of 10 cells was eventually installed until 1977, when many of the original technologies were outdated [Goldsmith, 2005]. Based on this trial network, Bell Labs worked out the first cellular network standard in the United States called Advanced Mobile Phone System (AMPS) [Young, 1979], which was successfully deployed in many countries and smoothly evolved into a second-generation cellular standard known as IS-54 (where IS stands for Interim Standard).

1.2 1G: The Birth of Cellular Network

In December 1979, the Japanese network operator Nippon Telegraph and Telephone (NTT) launched the first commercial cellular system in the world. The initial network comprised 88 cells covering all metropolitan area districts in Tokyo, and inter-cell handover was supported. It operated in the frequency band around 900 MHz and offered a total of 600 pairs of channels for Frequency-Division Duplexing (FDD) operation. The voice signal of each mobile user was transmitted over an analog channel with a bandwidth of 25 kHz. Within five years, the network was expanded to cover the entire population of Japan, making it the first country to provide a nationwide cellular communications service.

However, the early mobile stations in the NTT network were still car phones, which had to be fitted into automobiles and were first commercialized in the 1940s. Motorola demonstrated the world's first car call in October 1946, but the phone was too heavy (the original equipment weighs around 36 kg) and consumed too much power. In 1985, NTT released shoulder phones that were still bulky but at least can be carried freely by a human. The gifted engineer Martin Cooper led a Motorola team to develop the first cellphone prototype and demonstrated the first cellphone call at the New York City Hilton in midtown Manhattan on 3 April 1973. Ten years later, Motorola introduced its historic product - DynaTAC 8000X – the first commercial cellphone that was lightweight and small enough to carry. Owning a cellphone at that time was a symbol of affluence and social status since, for example, the Motorola DynaTAC 8000X was priced at $3 995 in 1984 with, in addition, an expensive subscription cost. Motorola played an exceptionally influential role in the early days of the development of cellphones. Followed its iconic DynaTAC 8000 series, the company released the world's first flip phone Motorola MicroTAC and then the first clamshell phone Motorola StarTAC, which was not only the world's smallest at the time but also most lightweight with an extreme weight of 105 g. These early days also witnessed the rise of Nokia to become the world's second-largest cellphone maker with the launch of their Cityman series followed by the Nokia 101 candy bar design as opposed to the previous "bricks" [Linge and Sutton, 2014].

While Motorola was developing the cellphone, Bell Labs worked out the AMPS system, which became the first cellular network standard in the United States [Frenkiel and Schwartz, 2010]. In October 1983, the United States eventually had got its first commercial cellular network launched by Ameritech in Chicago. Although it was later than other regions, the cellular service in the United States was offered through cellphones rather than car phones. In Europe, the Scandinavian countries pioneered the development of the first European cellular standard called Nordic Mobile Telephone (NMT). The first NMT network was rolled out in the Nordic countries of Norway and Sweden in 1981, followed by Denmark and Finland in the subsequent year. It was the first mobile network that can support international roaming. In 1985, the number of subscribers had grown to 110 000 in Scandinavia and Finland, made it the world's largest mobile network then. The initial NMT network was operated in 450 MHz (hence also known as NMT-450) and adopted a channel bandwidth of 25 kHz. Additional frequency bands, i.e. 890–915 MHz for the uplink and 935–960 MHz for the downlink, were allocated in 1986, and the system operating in these bands became known as NMT-900. As of 2021, according to Wikipedia, a limited NMT-450 network is still in operation in some remote regions of Russia to offer basic communication services in sparsely populated areas with long distances. In addition to NMT, European countries developed several different cellular standards, including Total Access Communication System (TACS) first implemented by the United Kingdom in 1983, C-450 in Germany (1985), and Radiocom 2000 in France (1986). However, the first-generation European standards were incompatible due to the adoption of different frequency bands, air interfaces, and communication protocols, as summarized in Table 1.1.

Among all first-generation analog standards, NMT and AMPS are regarded as two good representatives that achieved great success at that time, which are briefly introduced as follows:

1.2.1 Nordic Mobile Telephone (NMT)

Nordic Telecommunications Administrations developed the NMT standard to meet the heavy demand of voice service, which cannot be accommodated by the overcrowding mobile telephone networks then: Auto Radio Phone (ARP) in Finland, Mobile Telephony System (MTD) in Sweden and Denmark, and Public Land Mobile Telephony (OLT) Telephony in Norway. The principle technologies were ready by 1973, and the specifications for base stations were completed in 1977. In 1981, the first NMT system was launched in Norway and Sweden, followed by Denmark and Finland in the subsequent year. Using the FDD operation mode, the uplink transmission was assigned to the frequency band of 453–458 MHz while 463–468 MHz for the downlink. In 1986, another pair

Table 1.1 First-generation cellular standards.

Feature	AMPS	NMT	NTT	TACS	C-450	RC2000
Launch time	1983	1981	1979	1983	1985	1986
DL band (MHz)	869–894	463–468[a)]	870–885[b)]	935–960	460–465.74	424.8–428[c)]
UL band (MHz)	824–849	453–458	925–940	890–915	450–455.74	414.8–418
Bandwidth (kHz)	30	25	25	25	10	12.5
No. of channel	832	180	600	1 000	573	256
Multiple access	FDMA					
Duplexing	FDD					
Modulation	FM					

a) NMT also operated in the frequency bands around 900 MHz, known as NMT-900.
b) NTT also operated in several other frequency bands around 900 MHz.
c) Radiocom2000 also operated in several other frequency bands around 200 MHz.
Source: Adapted from Goldsmith [2005].

of frequency bands, i.e. 890–915 MHz and 935–960 MHz for the uplink and downlink, respectively, were allocated. The system employed Frequency-Division Multiple Access (FDMA) to accommodate a large number of mobile users. As a consequence, the spectrum was subdivided into a magnitude of narrow-band channels with a bandwidth of 25 kHz. The voice channels were analog, where the speech signals were modulated through Frequency Modulation (FM). Nevertheless, the control signaling between the base station and the mobile station was transmitted digitally, using Fast Frequency-Shift Keying (FFSK) modulation with a rate of up to 1200 bps. The cell sizes in an NMT network ranged from 2 to 30 km. To serve car phones, the system utilized a transmission power of up to 15 W (NMT-450) and 6 W (NMT-900), while the power was lower (up to 1 W) for mobile handsets. NMT was the first cellular system with fully automatic switching (dialing), and supported the handover among cells from the beginning. It was also the first cellular system to realize international roaming. The NMT specifications were free and open, allowing many companies such as Nokia and Ericsson to produce network equipment and pushing the deployment cost down.

1.2.2 Advanced Mobile Phone System (AMPS)

AMPS was developed in the United States primarily by Bell Labs, inspired by the heavily congested mobile telephone system. Originated in the cellular concept proposed in 1947, it underwent quite a long journey to become a practical network. The system design had been almost completed in the 1960s, followed by an extensive trial (technical and commercial) to optimize the system parameters and verify the basic planning rules for a cellular layout. In 1978, Bell Labs set up a large-scale and fully operational trial network, working in cooperation with Illinois Bell Telephone Co., the American Telephone and Telegraph Co. (AT&T), and the Western Electric Co. The trial network consisted of 10 cells to cover approximately 3 000 square miles in the Chicago, IL area, aiming to provide a capacity for more than 2 000 users [Ehrlich, 1979]. It was not until 1983 that commercial operation licenses were issued when the FCC allocated an initial spectrum of 40 MHz (later increased to 50 MHz) for analog cellular networks. The downlink and uplink transmission were separated using FDD, where a pair of frequency bands on 824–849 and 869–894 MHz were assigned. The spectrum was subdivided into a total of 416 paired channels consisting of 21 control channels and 395 voice channels. The speech signal of a mobile user was tuned to the carrier frequency using the FM analog modulation and transmitted over a 30 kHz channel. Although AMPS was an analog cellular system, its control channels were already digitized. Control signaling was exchanged between a base station and mobile stations at a data rate of 10 kbps. The data was modulated using Frequency-Shift Keying (FSK) and the Manchester encoding was used for error correction.

1.3 2G: From Analog to Digital

Similar to the first generation of anything, the first-generation cellular system was not called 1G until the term 3G was adopted to name the third-generation system around 20 years later. Although 1G opened the era of mobile cellular communications, it was considered primitive and exhibited many deficiencies such as

- Worse voice quality
- Limited system capacity
- No security protection
- Limited international roaming
- Poor handover reliability
- Bulky and expensive handsets
- Short battery life

Consequently, the mobile industry initiated the development of second-generation digital systems in the early 1980s, and it gradually replaced the first-generation analog systems in the 1990s. The digital cellular standards in this generation included Global System for Mobile (GSM) in Europe, Digital Advanced Mobile Phone System (D-AMPS) and IS-95 in the United States, and Personal Digital Cellular (PDC) in Japan [Mishra, 2005].

Digitization

The transition from the first-generation to second-generation cellular system was driven by digital technology. A digital system can achieve a higher capacity than an analog system since digital communications can apply more spectral-efficient digital modulation and more efficient multiple-access techniques. Digitization facilitates the compression of voice signals, the encryption of information against eavesdropping, and the support for data services. In addition, digital components are more powerful, more lightweight, smaller, cheaper, and more power-efficient than analog components.

1.3.1 Global System for Mobile Communications (GSM)

The incompatibility among various European systems made it different for the travelers among European countries to get continuous communication service with a single analog phone. It motivated the necessity for a uniform European standard and unified frequency allocation throughout Europe. As early as 1982, the Conference of European Postal and Telecommunications (CEPT) set up a working group called the Global System for Mobile (the initial meaning of GSM) to coordinate the development work. From 1982 to 1985, discussions were held in the GSM group to select between an analog and a digital system. After multiple field trials, it was decided to develop a digital cellular system based on narrow-band Time-Division Multiple Access (TDMA). The requirements for this pan-European system, such as good subjective voice quality, low terminal and service cost, and international roaming, were defined. In 1988, the CEPT formed the European Telecommunications Standards Institute (ETSI), and then the responsibility for specifying the standard was transferred to ETSI. In 1990, the Phase I recommendations for the Global System for Mobile communications (GSM) was released. Meanwhile, a variant of GSM operating in a higher frequency band, known as Digital Cellular System at 1800 MHz (DCS-1800), was standardized within ETSI and approved in February 1991 [Mouly and Pautet, 1995]. In addition to the basic voice service, GSM terminals can connect with the Integrated Services Digital Network (ISDN) for various data services with a rate of 9.6 kbps. The commercial operation of the first GSM network started in Finland. On 1 July 1991, the Finnish Prime Minister Harri Holkeri made the world's first GSM call on the Radiolinja mobile network built with the equipment from Nokia and Siemens. Since then, GSM has rapidly gained acceptance and became the dominant 2G digital cellular standard [Vriendt et al., 2002]. It achieved remarkable commercial success, with a global market share of more than 90%. By early 2004, more than 1 billion population in more than 200 countries and territories enjoyed their mobile telephony services thanks to GSM.

1.3.2 Digital Advanced Mobile Phone System (D-AMPS)

Due to its economy of scale, the AMPS standard achieved a relatively better position over sporadic and competitive European standards in the era of 1G. Nevertheless, the United States did not continue the same success in the second round. The development of the second-generation digital cellular fell into a raged debate on the selection of spectrum sharing techniques between TDMA and Code-Division Multiple Access (CDMA). The result of this debate was two incompatible systems: IS-54 (and its evolution known as IS-136) versus IS-95. IS-54 and IS-136 constituted D-AMPS, which was the digital advancement of the existing AMPS systems in the United States. D-AMPS inherited the basic architecture and signaling protocols from its predecessor, allowing for a smooth transition from analog to digital. The D-AMPS network was deployed in the same frequency bands of AMPS, i.e. 869–894 MHz for the downlink and 824–849 MHz for the uplink. But each 30 kHz channel was further subdivided into three time slots using TDMA. Capacity was tripled by multiplexing compressed voice signals from three users over a single analog channel. The specification of IS-54 was completed in 1992, and was deployed in the United States and Canada ever since its first commercial launch in 1993. It was enhanced over time and these enhancements evolved into the IS-136 standard. IS-136 introduced several new features to the original IS-54 standard, including circuit-switched data, text messaging, and the support of operating in 1900 MHz. IS-136 opened the possibility for an all-digital TDMA system instead of the dual-mode operation adopted by its predecessor.

1.3.3 Interim Standard 95 (IS-95)

CDMA has some unique technical advantages over TDMA for cellular systems, e.g. higher system capacity and simple frequency planning due to universal frequency reuse, high quality of service during soft handover, no hard limit on the number of users (soft capacity), the ability to exploit voice activity to reduce the aggregated interference automatically, and improved robustness using noise-like spread-spectrum signals. Qualcomm developed the first CDMA-based cellular system, and the initial specifications of the system were finalized in 1993. The Telecommunications Industry Association (TIA) and Electronic Industries Alliance (EIA) of the United States approved it as a digital standard in 1995, hence named IS-95 or IS-95A. In October 1995, Hutchison Telephone launched the world's first commercial CDMA cellular network in Hong Kong, under the name of cdmaOne. In contrast to previous narrow-band mobile communications, it was a wideband system that spreads information bits over a signal bandwidth of 1.25 MHz using the direct-sequence spread-spectrum technique. The CDMA system required complicated air interfaces and communication protocols, e.g. the

Rake receiver was adopted to mitigate the effect of multi-path transmission. Due to multi-user interference and inter-cell interference, the system performance depended heavily on accurate power control, especially in the uplink, to compensate for the near-far effect. A power-control bit was transmitted 800 times per second on the forward link to instruct a mobile station to adjust its transmit power with a granularity of 1 dB. The enhanced version was IS-95B, also called 2.5G of CDMA technology, which combined the standards IS-95, ANSI-J-STD-008, and TSB-74. The standardization of IS-95B was completed in 1997 and the world's first IS-95B commercial network was launched by a South Korean operator in 1998. It provided a higher data rate through code aggregation, where a base station can assign up to eight code channels to a single mobile station, increasing the achievable rate from 11.4 kbps in IS-95A to 115 kbps. There was much debate about the relative merits of the IS-54 and IS-95 standards throughout the early 1990s, claiming that IS-95 could achieve 20 times the capacity of AMPS, whereas IS-54 could only achieve three times this capacity. In the end, both systems turned out to achieve approximately the same capacity increase over AMPS [Goldsmith, 2005].

1.3.4 Personal Digital Cellular (PDC)

Japan independently developed its digital cellular standard known as PDC, exclusively deployed in Japan. Similar to D-AMPS and GSM, PDC adopted TDMA as the multiple-access technique. To be compatible with the Japanese analog systems, it selected a signal bandwidth of 25 kHz for voice channels. Each channel was divided into three time slots for full-rate (11.2 kbps) or six time slots for half-rate (5.6 kbps) voice codecs. The Research and Development Center for Radio System (RCR), later became the Association of Radio Industries and Businesses (ARIB), completed the specifications in April 1991. Using the network equipment manufactured by NEC, Motorola, and Ericsson, NTT DoCoMo launched its digital service in March 1993. After a peak of nearly 80 million subscribers, it was slowly phased out in favor of 3G technologies and was shut down on April 1, 2012. The PDC network offered mobile voice services (full- and half-rate), supplementary services (call waiting, voice mail, three-way calling, call forwarding, etc.), circuit-switched data service (up to 9.6 kbps), and packet-switched data service (up to 28.8 kbps). Regardless of its isolation from the rest of the world, the Japanese 2G network fostered an eye-catching innovation known as i-mode, which was regarded as a pioneer of mobile Internet (Tables 1.2–1.4).

1.3.5 General Packet Radio Service (GPRS)

In addition to the improved security due to digital encryption and significantly increased system capacity over their predecessors, the milestone progress of 2G

Table 1.2 Second-generation cellular standards.

	GSM	D-AMPS	PDC	IS-95
Launch year	1991	1993	1993	1995
DL band (MHz)	935–960	869–894	940–960, 1 477–1 501	869–894
UL band (MHz)	890–915	824–849	810–830, 1 429–1 453	824–849
Bandwidth (kHz)	200	30	25	1 250
User capacity	1 000	2 500	3000	~2 500 (soft)
Multiple access	TDMA			CDMA
Receiver	Equalizer			RAKE
Duplexing	FDD			
Modulation	GMSK	π/4-DPSK	π/4-DPSK	BPSK/QPSK
Speech (kbps)	13	7.95	11.2 (full)/5.6 (half)	1.2–9.6 (variable)

cellular was the introduction of data service into the mobile network. In 1992, for the first time, Short Messaging Service (SMS), which supports a data rate of 9.6 kbps, was born. Neil Papworth, a 22-year-old software engineer working at Vodafone, sent the world's first text message on 3 December 1992 when he typed "Merry Christmas" from a computer to Richard Jarvis on an Orbitel 901 handset. With the phenomenal success of SMS and the rising demand for accessing the Internet via mobile phones and laptop computers, the 2G cellular standards evolved to enhance the capability of carrying High-Rate Packet Data (HRPD) services.

ETSI developed General Packet Radio Service (GPRS) in response to the earlier Cellular Digital Packet Data (CDPD), overlaying the AMPS system to provide a rate of 19.2 kbps, and Japanese i-mode services. The Cellular Packet Radio (CELLPAC) protocol that introduced packet-switching in GSM was the root for the specification of GPRS starting from 1993 [Walke, 2003]. In June 2000, British Telecom Cellnet launched the world's first commercial GPRS network in the United Kingdom. GPRS is an overlaying packet-switched data network on the circuit-switched GSM network. Relying on the legacy air interface, an operator only needs to install some network nodes to upgrade a voice-only GSM network to a voice-plus-data GPRS network. Base station controllers separate the data and voice traffic, and direct the data to GPRS support nodes connected to the data network. Operating in a best-effort style, GPRS typically reached a data rate of 40 kbps in the downlink and 14 kbps in the uplink by aggregating multiple time slots into one bearer. Enhancement in later specifications can theoretically achieve a peak rate of 171.2 kbps by aggregating eight time slots at the same time for a single user.

1.3.6 Enhanced Data Rates for GSM Evolution (EDGE)

On the one hand, GPRS exhibited some limitations, such as low practical data rates much lower than the theoretical values. On the other hand, the mobile operators, who failed to win a 3G license, needed a further-enhanced GPRS standard to offer data services at speeds near those available on 3G networks. Enhanced Data Rates for GSM Evolution (EDGE) was first developed by the ETSI, as an evolution of GPRS in 1997. Although EDGE reused the GSM carrier bandwidth and time slot structure, it was not restricted to GSM cellular systems. Instead, it aimed to become a generic technology facilitating an evolution of existing cellular systems toward third-generation capabilities [Furuskar et al., 1999]. After evaluating several different proposals, the Universal Wireless Communications Consortium (UWCC) approved EDGE in January 1998 as the outdoor component of IS-136HS to provide 384 kbps data services. The first commercial EDGE network was launched in 2003 by AT&T in the United States. With the introduction of a higher-order modulation scheme named eight phase-shift keying (8PSK), opposed to Gaussian Minimum-Shift Keying (GMSK) in its predecessors, it can support maximal data rate up to 470 kbps. Several new techniques, including link adaptation, Hybrid Automatic Repeat Request (HARQ) with soft combining, and advanced scheduling, were first applied in EDGE, followed by Wideband Code-Division Multiple Access (WCDMA), CDMA2000, and other standards.

Meanwhile, the IS-54 and IS-136 systems provided a data rate of up to 60 kbps by aggregating time slots and using high-order modulation. The further evolution of the IS-136 standard was called IS-136HS (high-speed), based on EDGE. It increased the data throughput of IS-136 systems to over 470 kbps per carrier. The initial IS-95 system supported circuit-mode and packet-mode data services at a data rate of 14.4 kbps. Without breaking the legacy air interface design to maintain strict backward-compatibility, it was upgraded to IS-95B that offered an increased data rate of 115 kbps [Knisely et al., 1998].

The transition from 1G analog to 2G digital also facilitated the innovation of mobile terminals, where much smaller, lighter, cheaper, and power-efficient cell phones were popularized at an extraordinary pace. Mobile phones moved from being commercial users to general users as an essential part of modern living. Nokia successfully recognized the desire of people to turn mobile phones into personalized devices. In 1994, Nokia released the first cell phone to use the iconic ring-tone – Nokia 2110, the first cell phone allowing the user to change the phone's covers to reflect their mood or style – Nokia 5110, and the first to feature the mobile game Snake – Nokia 6110. As a consequence, Nokia achieved the dominant market share in the world's cell phone market. In 2002, the world had completed the transition to digital cellular networks, and the number of mobile subscribers surpassed that of the fixed-line telephone subscribers for the first time, making cellular networks the dominant technique to provide communication service.

1.4 3G: From Voice to Data-Centric

Second-generation digital systems were designed to address the weaknesses, such as limited system capacity, easy eavesdropping, and worse voice quality, in the first-generation systems. However, standards like GSM, IS-95, and IS-136 were still designed for voice communications but performed not well for data service.

Data-Centric Cellular Network
The proliferation of Internet-based services, such as web browsing, multimedia messaging, email, interactive gaming, and high-fidelity audio and video streaming, and the expansion of these services from wired networks to mobile networks, imposed a need for data-optimized cellular systems to replace previous voice-centric cellular systems.

Incompatible mobile environment and fragmented spectrum usage that annoyed the previous generations motivated the International Telecommunications Union (ITU) to begin the effort on a global standard with full interoperability and interworking in the 1980s. In 1990, the ITU released the first recommendation on the Future Public Land Mobile Telecommunications System (FPLMTS). FPLMTS was renamed to the International Mobile Telecommunications-2000 (IMT-2000) [ITU-R M.1225, 1997] in the late 1990s since the old acronym was hard to pronounce. Meanwhile, the World Radio Conference held in February 1992 identified 230 MHz spectrum in the bands 1885–2025 MHz and 2110–2200 MHz for IMT-2000 on a worldwide basis. IMT-2000 recommendations defined the minimal technical requirements of the 3G system, including high data rate, asymmetric data transmission, global roaming, multiple simultaneous services, improved voice quality, security, and greater capacity. The evaluation criteria specified in International Telecommunication Union Radiocommunication (ITU-R) M.1225 [ITU-R M.1225, 1997] set the target data rates for the 3G circuit-switched and packet-switched data services:

- Up to 2 Mbps for an indoor environment.
- Up to 144 kbps for outdoor-to-indoor and pedestrian environments.
- Up to 64 kbps for a vehicular environment.

Nevertheless, the ITU did not specify technological solutions to meet these requirements but only solicited proposals from interested organizations. Based on the successful standardization of GSM, the ETSI initiated a new organization called the Third Generation Partnership Project (3GPP) together with other standard development organizations across the world, including ARIB (Japan), ATIS (USA), CCSA (China), TTA (South Korea), and TTC (Japan). At the same time, another group in the United States formed the Third Generation Partnership Project 2 (3GPP2), intended to the specifications for a 3G system based on the evolution of IS-95. Although some differences remained, both 3GPP and 3GPP2 selected CDMA as the underlying baseline technology. The standard developed by 3GPP was WCDMA or Universal Mobile Telecommunications System (UMTS). 3GPP2 focused on the development of CDMA2000, which reused the spectrum bands of IS-95 and inherited the bandwidth set of 1.25 MHz. In 1998, the ITU received numerous technical proposals, among which five standards were approved for terrestrial service, i.e. UTRA FDD, UTRA Time-Division Duplex (TDD), CDMA2000, TDMA Single-Carrier, and FDMA/TDMA. In 2007, Worldwide Interoperability for Microwave Access (WiMAX) specified by IEEE 802.16 specifications was approved by the ITU as the sixth IMT-2000 standard, also known as IMT2000 OFDMA TDD WMAN. Unlike other 3G standards based on CDMA, WiMax adopted more pre-4G technologies such as orthogonal frequency-division multiplexing (OFDM), multiple-input multiple-output multi-input multi-output (MIMO), and low-density parity-check (LDPC) coding. IMT-2000 TDMA Single-Carrier also called Universal Wireless Communications 136 (UWC-136), developed by a consortium consisting of more than 85 wireless network operators and vendors, is based on TDMA for backward compatible with the IS-136 standard. Digital Enhanced Cordless Telecommunications (DECT) was also called IMT-2000 FDMA/TDMA, which was developed under DECT Forum and ETSI. Although UWC-136 and DECT were also approved 3G standards by the ITU, they received fewer supports from the industry and were not widely deployed. The ITU-R family of IMT-2000 terrestrial radio interface standards are illustrated in Figure 1.1.

1.4.1 Wideband Code-Division Multiple Access (WCDMA)

In the late 1990s, NTT DoCoMo developed Wideband CDMA technology for their 3G system known as Freedom of Mobile Multimedia Access (FOMA). WCDMA only defined the air-interface part, therefore also named as Universal Terrestrial Radio Access (UTRA). WCDMA was selected as the air interface of UMTS, as the 3G successor to GSM. Different systems, including FOMA, UMTS, and J-Phone, shared WCDMA air interface but have different protocols for a complete stack of communication standards. 3GPP submitted it as an IMT-2000 proposal, and the ITU-R approved it as part of the IMT-2000 family standards. It employed direct-sequence code-division multiple access with a chip rate of 3.84 Mcps. The radio access specifications provided both FDD and TDD variants, utilizing a 5 MHz channel to achieve peak rates of up to 5 Mbps. In October 2001, NTT DoCoMo launched the first commercial FOMA network in Japan as the successor to i-mode. In many European countries, mobile operators acquired a license for the 3G spectrum and had to pay enormous fees in auctions. For example, the

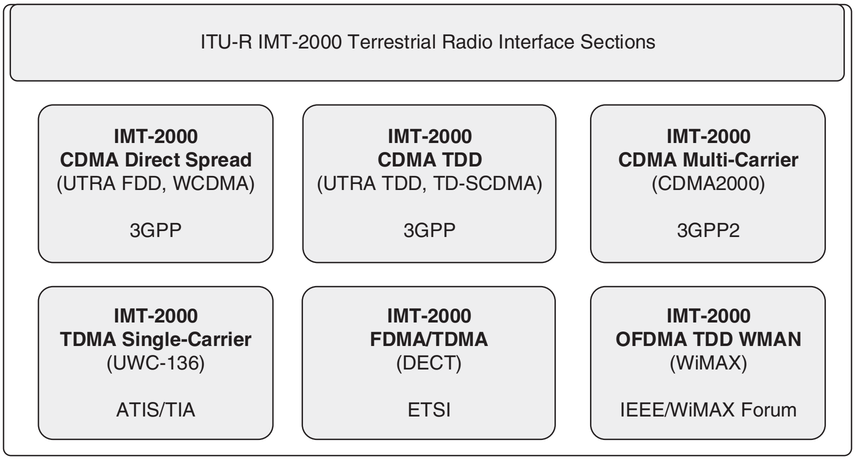

Figure 1.1 IMT-2000 standards approved by ITU-R [ITU-R M.1457, 2000]. Source: Data from ITU-R M.1457 [2000].

mobile operators of the United Kingdom spent 33 billion USD in the auction of April 2000, and 47.5 billion USD was recorded in German auction later that year. Such a high financial pressure of mobile operators raised by the high licensing cost resulted in a delay of the commercial roll-out of European 3G networks. As an example, the United Kingdom's first commercial 3G network was deployed by Hutchison Telecom as late as March 2003.

WCDMA specified in Release 99 and Release 4 of the specifications contains all technical features to satisfy the IMT-2000 requirements, but further enhancement had never stopped, as shown in Figure 1.2. High Speed Packet Access (HSPA) appeared in 2002 as the first significant evolution of the WCDMA radio interface.

- *Release 5* increased the downlink capability with a rate of up to 14 MHz, known as High Speed Downlink Packet Access (HSDPA). To achieve this, it introduced a set of technical features, including shared-channel transmission, channel-dependent scheduling, higher-order modulation (i.e. 16QAM), H-Automatic Repeat Request (ARQ) with soft combining, and link adaptation.
- *Release 6* was finalized in March 2005 added the enhancement known as High Speed Uplink Packet Access (HSUPA), offering a rate of 5.74 MHz in the uplink.
- *Release 7* published in September 2007, as a further evolution of HSPA called HSPA Evolution or HSPA+. It utilized multiple antennas technique (2x2 MIMO) and higher-level modulation (i.e. 16QAM in the uplink and 64QAM in the downlink), to achieve 28 Mbps in the downlink and 11 Mbps in the uplink over a bandwidth of 5 MHz.
- *Release 8* enabled the simultaneous usage of two-layer spatial multiplexing and 64QAM modulation in the downlink. It employed carrier aggregation in a similar way as later done for long-term evolution (LTE), thereby increasing

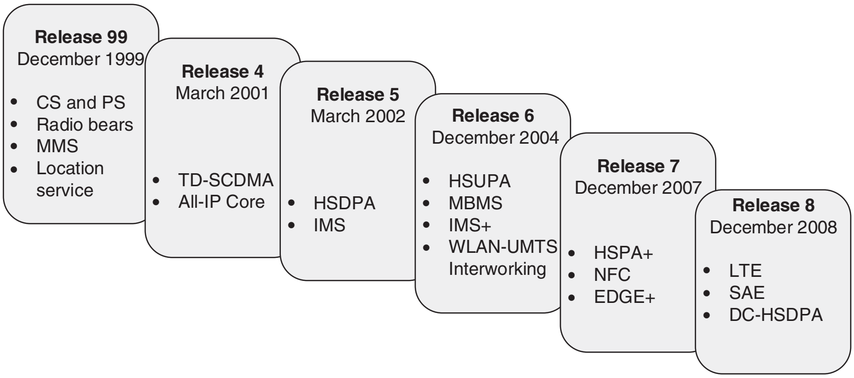

Figure 1.2 Releases of 3GPP specifications for WCDMA.

the maximal bandwidth 10 MHz. Dual-carrier HSDPA can double data rates to 56 Mbps in the downlink by aggregating two carrier channels.

- *Release 9* enhanced the uplink by introducing two aggregated carriers, leading to a rate of 22 Mbps in the uplink.
- *Release 10* can achieve the downlink peak data rate of 168 Mbps by adding the support of aggregating four component carriers for the maximal bandwidth of 20 MHz [Dahlman et al., 2011].

1.4.2 Code-Division Multiple Access 2000 (CDMA2000)

IS-95 was the first cellular system that employed CDMA technology, and therefore it was easier to evolve into a CDMA-based 3G standard. When it became a global IMT-2000 standard, the name was changed to CDMA2000, and the standardization work was transferred from the US TIA to 3GPP2. Being a sister organization of 3GPP, 3GPP2 pushed forward the CDMA2000 technology with an evolution path similar to that of WCMDA. The focus was shifted from circuit-switched voice communications to packet-switched data services. Two parallel evolutionary paths, as demonstrated in Figure 1.3, were initiated to improve the support of data transmission further. The primary path was *Evolution-Data Only (EV-DO)*, or also interpreted as *Evolution – Data Optimized*. In contrast, another path dedicated to the simultaneous support of both circuit-switched and packet-switched services on the same carrier, hence referred to as *Evolution for integrated Data and Voice (EV-DV)* [Attar et al., 2006].

- *CDMA2000 1x*: The initial version of IMT-2000 CDMA Multi-Carrier approved by the ITU-R supported two operation modes: single carrier (CDMA2000 1x) and multiple carriers (CDMA2000 3x). Although the 3x mode was an essential component of the submission of CDMA2000 to the ITU-R, it was

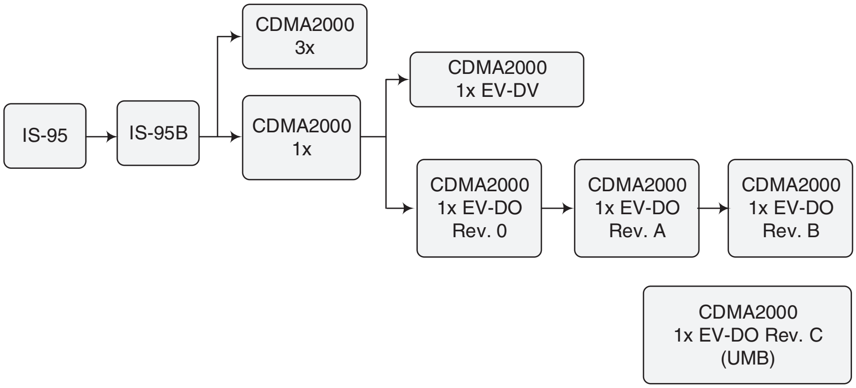

Figure 1.3 The evolution path of CDMA2000.

never commercially deployed in a large-scale network. CDMA2000 1x was a fully backward-compatible advance of IS-95, inheriting the basic design of direct-sequence spread spectrum and the channel bandwidth of 1.25 MHz. It added several enhancements over the earlier versions of IS-95 to improve spectral efficiency and offer higher data rates. Most importantly, it provided a structure opening the possibility for further evolution of packet-switched data services. CDMA2000 1x can be deployed on the IS-95 frequency bands so that an IS-95 network operator can smoothly upgrade from 2G to 3G without the need to acquire a license for the 3G spectrum. In October 2000, SK Telecom rolled out the world's first commercial CDMA2000 1X network in South Korea. As of 2014, the CDMA Development Group stated that 314 operators in 118 countries had offered CDMA2000 1X or 1xEV-DO services.

- *CDMA2000 1x EV-DO Revision 0*: The 1x version of CDMA2000 was evolved along different paths, resulting in two options: CDMA2000 1xEV-DV and CDMA2000 1xEV-DO. The former focused on the improvement of voice capacity and received limited development under 3GPP2. In contrast, EV-DO played as a main evolution track and went through several evolutionary steps in Revision 0, Revision A, Revision B, and Revision C. CDMA2000 1x EV-DO has later also been named HRPD. EV-DO Revision 0 re-designed the uplink and downlink structure of CDMA2000 1x, optimized for packet-switched data transmission while removed the constraint of supporting circuit-switched voice communications. An operator would deploy an additional carrier for EV-DO, separating voice and packet-data connections on different carriers. 3GPP2 added a set of data-optimized technologies into the Revision 0 of CDMA2000 EV-DO, including shared-channel transmission, channel-dependent scheduling, short Transmission Time Interval (TTI), link adaptation, higher-order modulation (i.e. 16QAM in the downlink), HARQ, virtual soft handover, and receive diversity. These techniques were also adopted by 3GPP for the evolution of HSPA. Thanks to a new air interface and a separate channel used only for data transmission, a data rate of 2.4 Mbps in the forward link was achieved while 153 kbps on the reverse link over a 1.25 MHz carrier.

- *CDMA2000 1x EV-DO Revision A*: The next evolution after Revision 0 was named Revision A, rather than Revision 1, which focused on the enhancement of the uplink similar to HSUPA in 3GPP. The forward link of Revision A is similar to that of Revision 0, but it also included some updates, increasing the data rate from 2.4 to 3.1 Mbps. In the reverse link, higher-order modulation (i.e. QPSK and optional support of 8PSK), in contrast to BPSK used in Revision 0, as well as HARQ, were introduced, achieving the uplink rate of up to 1.8 Mbps. Besides, the utilize of smaller packet sizes and a shorter TTI enabled a lower latency of up to 50% compared with its predecessor for well supporting of voice over IP (VoIP) and delay-sensitive data services.
- *CDMA2000 1x EV-DO Revision B*: The further enhanced version was Revision B, which supports higher data rates by using multiple carriers. Up to 16 carriers can be aggregated to form a 20 MHz bandwidth, achieving a theoretical rate of up to 46.5 Mbps. Due to the constraint of cost, hardware size, and battery life, the mobile terminal in a Revision B network supports up to three carriers, resulting in a peak rate of 9.3 Mbps. The radio interface of Revision B was backward compatible with Revision 0 and Revision A, making it possible for a multi-carrier network to further support legacy single-carrier terminals. It supported an asymmetric operation where carriers do not have to be symmetrically allocated between the downlink and the uplink. For asymmetric applications such as file download and video streaming, more carriers can be used for the forward link. One reverse link can carry control signaling and feedback information for multiple forward links, reducing the amount of uplink signaling overhead.
- *CDMA2000 1x EV-DO Revision C*: The next step was 1x EV-DO Revision C, also known as Ultra Mobile Broadband (UMB). Adopting Loosely Backward Compatible (LBC) option, Revision C is not compatible with the previous revisions of CDMA2000 specifications. The objectives for designing a disruptive air interface were to achieve higher peak rates, improved spectral efficiency, lower latency, and enhanced user experiences for delay-sensitive data applications, like the development of LTE in 3GPP. The significant new features in Revision C are the introduction of typical 4G technologies, namely, OFDM and MIMO. OFDM multi-carrier transmission selected a subcarrier spacing of 9.6 kHz with different Fast Fourier Transform (FFT) sizes (128, 256, 512, 1024, and 2048) to flexibly support various transmission bandwidths. Spatial multiplexing supported up to four transmission layers in the forward link but it was only supported in conjunction with OFDM. In the reverse link, up to two spatial layers were

Table 1.3 Third-generation cellular standards.

Parameter	WCDMA	CDMA2000	TD-SCDMA	WiMAX
Version	Release 99	1x	Release 4	IEEE802.16e
Launch time	2001	2000	2009	2006
Bandwidth (MHz)	5	1.25	1.6	1.25/5/10/20
Multi-access	CDMA			OFDMA
Duplexing	FDD	FDD	TDD	TDD
Chip rate (Mcps)	3.84	1.2288	1.28	N/A
Power control	1500 Hz	800 Hz	200 Hz	N/A
Frame length (ms)	10	20	10	5
Modulation	QPSK (DL)/BPSK (UL)		~8 PSK	~64 QAM
Channel coding	Turbo codes			Turbo/LDPC

specified with codebook-based precoding under the control of a base station. Using a bandwidth of 20 MHz, the maximal rates are 260 Mbps in the forward link and 70 Mbps in the reverse link. CDMA2000 and WCDMA competed for the 3G market worldwide in the first several years of 3G deployment. Regardless of the incompatibility with legacy GSM standards, late introduction, and the high upgrade cost of deploying an all-new air-interface technology, WCDMA has won this competition and eventually became the dominant 3G standard. As a consequence, the supports for the evolution of CDMA2000 gradually became weak. In the 3GPP2 camp, UMB was the target to the planned 4G successor of CDMA2000, competed with LTE in 3GPP. However, Qualcomm, the main stakeholder of UMB, announced to cease the further evolution of CDMA2000 technologies in November 2008. 3GPP2 had its last activity in 2013, and the group has been dormant ever since.

1.4.3 Time Division-Synchronous Code-Division Multiple Access (TD-SCDMA)

In parallel to the development of UTRA FDD/WCDMA and its evolution to HSPA, 3GPP also worked on the TDD version of UTRA. Regardless of the similar high-layer protocols between FDD and TDD, the physical-layer designs were quite different. For historical reasons, there were three variants with different chip rates. The initial version of UTRA TDD adopted the chip rate of 3.84 Mcps, and 7.68 and 1.28 Mcps were added later. UTRA low chip rate (1.28 Mcps) TDD, also called Time Division-Synchronous Code Division Multiple Access (TD-SCDMA), is substantially different from the other two. TD-SCDMA was developed as an industry standard under the lead of the Chinese Academy of Telecommunications Technology (CATT). In March 2001, it was approved to merge into Release 4 of the 3GPP specifications as an alternative UTRA TDD version. The significant difference between TD-SCDMA and the other two 3G standards (WCDMA and CDMA2000) is its use of TDD operation instead of FDD for duplex signaling. It adopted a signal bandwidth of 1.6 MHz, 8PSK modulation, and a shorter TTI of 5 ms. Some technical features such as multi-frequency operation and smart antenna/beamforming support with eight antennas were introduced by this system. Of the three versions, TD-SCDMA was the only UTRA TDD standard deployed on a large scale, with the other two being limited to niche deployment. China Mobile, the world's biggest mobile operator in terms of the number of subscribers, was granted a 3G license in early 2009 for operating a TD-SCDMA network. The unique TD-SCDMA deployment worldwide finally become a network consisting of around 500 000 base stations and the peak number of subscribers reached approximately 250 million. Although this technology was exclusively applied in China, it promoted TDD systems' advantages and pushed forward the development of a TDD version of 4G known as TD-LTE or LTE TDD. The HSPA enhancements of TD-SCDMA were similar to those applied to UTRA FDD, such as the application of high-order modulation (16QAM) and hybrid ARQ.

1.4.4 Worldwide Interoperability for Microwave Access (WiMAX)

The IEEE 802.16 specifications were developed by the Institute of Electrical and Electronics Engineers (IEEE) under the umbrella of Wireless Metropolitan Area Network (WMAN). The initial version in 2001 was designed for line-of-sight communications in the millimeter-wave frequency range of 10–60 GHz, targeting fixed Wireless Broadband (WiBro) access. In 2003, the enhanced version called IEEE 802.16a introduced the support for non-line-of-sight operation over the low-frequency bands of 2–11 GHz, but still limited to fixed-wireless-access applications. The monumental milestone was the IEEE 802.16e-2005 specification released in 2005 as the first mobile WiMAX system [Etemad, 2008]. Empowered by cutting-edge technologies at that time, it offered the peak data rates of 128 Mbps in the downlink and 56 Mbps in the uplink over a 20 MHz channel. The first commercial network was deployed in South Korea in 2006 (branded as WiBro) and then deployed in many parts of the world.

The IEEE 802.16 specifications usually provide the specifications of the physical and Medium Access Control (MAC) layers instead of the overall communication protocol stack. Furthermore, IEEE 802.16 specifications contain multiple alternatives for the basic physical-layer transmission scheme. Implementing all these options and alternative features in a mobile system was not necessary. The WiMAX Forum is an industry-led, non-profit alliance formed to promote and certify compatibility and interoperability of IEEE 802.16-based products. Its responsibility was to select technical features from the full set of features defined by IEEE 802.16 specifications to form a complete and implementable standard called WiMAX System Profile. The first such profile, WiMAX Release 1.0, was published in 2007, with the second profile, Release 1.5, finalized in 2009. IEEE 802.16e, also referred to as Mobile WiMAX, was submitted to the ITU-R as a proposal for IMT-2000. It was approved in 2007 by the ITU as IMT-2000 OFDMA TDD WMAN, in parallel with WCDMA, CDMA2000, and TD-SCDMA.

Although IEEE 802.16 provided several alternatives for the basic physical-layer transmission scheme, including both OFDM and single-carrier transmission, Mobile WiMAX is based on OFDM transmission. Like LTE, IEEE 802.16e improve spectrum flexibility by adopting variable bandwidths, i.e. 1.25, 5, 10, and 20 MHz. With a common subcarrier spacing of 10.94 kHz, only scaling the number of subcarriers (128, 512, 1024 and 2048) within the transmission bandwidth. IEEE 802.16e specified both TDD and FDD, including the possibility for half-duplex FDD, whereas the first version of Mobile WiMAX merely support the TDD operation, where a 5 ms frame is divided into downlink and uplink part, together consisting of 48 OFDM symbols. Similar to LTE, Mobile WiMAX supports QPSK, 16QAM, and 64QAM modulation, and link adaptation (adaptive modulation and coding) in terms of instantaneous channel conditions. The 802.16e specifications support various channel coding schemes, including Turbo codes, similar to HSPA and LTE, and LDPC codes. However, Mobile WiMAX only supports Turbo codes.

Video content and web browsing raised the need for larger and better screen displays, fostering the revolution of the mobile terminal. The first smartphone was the IBM Simon released in 1994, followed by Nokia 9000 released in 1996, combining email, word processor, diary, and QWERTY keyboard. On 7 January 2007, Steve Jobs announced that Apple was entering the mobile phone market and, by considering the mobile as a computer first and phone second, brought a whole new insight to handset design. The Apple iPhone proved to be a disruptive piece of technology that redefined mobile phone design and introduced the world to the APPlication (APP) – even though the first model was only a 2G device [Linge and Sutton, 2014].

1.5 4G: Mobile Internet

The number of mobile subscribers grew tremendously in the first decade of the twenty-first century. The landmark for the first billion achieved in 2002, but the number boomed quickly to over 5 billion in 2010. Another driving force for the fourth-generation cellular system was the explosive growth of traffic brought by mobile broadband. In cellular networks, for the first time, the data traffic exceeded the voice traffic and was expected to saturate 3G networks soon. In addition, the proliferation of Internet-based services on mobile devices imposed a significant challenge on cellular networks that were optimized for voice communications. Since the 2.5G system, cellular networks had to simultaneously operate two parallel infrastructures: a packet-switched network for data services and a circuit-switched network for voice calls.

All-IP Cellular Network

The 4G cellular system was driven toward end-to-end all-IP architecture such that Internet-based services can be well supported. For the first time in the history of cellular networks, the circuit-switched network was thoroughly abandoned, and only a packet-switched network was provided for more flexible and efficient operation.

The 3G standardization bodies such as 3GPP, 3GPP2, WiMAX, and IEEE were working on the enhancements of 3G standards toward 4G, using advanced air-interface technologies and all-IP network infrastructure. To ensure the competitiveness of UMTS, 3GPP initiated the study item of *LTE* air interface, also known as Evolved Universal Terrestrial Radio Access (E-UTRA), in 2004. In December 2008, the first release (Release 8) of the LTE air interface and its core network called the Evolved Packet Core (EPC) was completed, followed by an enhanced version (Release 9) frozen in December 2009. Similar to the development of IMT-2000, the ITU-R WP5D defined the minimal technical requirements for the 4G system, named the International Mobile Telecommunications Advanced (IMT-Advanced) in 2008. However, since LTE cannot fully comply with the requirements of IMT-Advanced, e.g. the peak data rate of 1 Gbps for low mobility and 100 Mbps for high mobility, 3GPP then continued to work on an enhanced version known as long-term evolution-advanced (LTE-Advanced) from 2009. Meanwhile, the WiMAX standard continuously evolved under the development of IEEE and WiMAX Forum. The specifications of WirelessMAN-Advanced (also known as Mobile WiMAX Release 2.0) were completed in 2011 to comply with IMT-Advanced. Significant enhancements were introduced on IEEE 802.16e-2005 to form a new standard named IEEE 802.16m-2011. IEEE and WiMAX Forum submitted IEEE 802.16m-2011 to the ITU as one of the IMT-Advanced proposals, competing with LTE-Advanced. In addition, 3GPP2 worked on the development of UMB as a fourth-generation successor to CDMA2000. However, Qualcomm, the leading sponsor of UMB, announced the end of developing this technology in November 2008, favoring LTE instead. As a result, 3GPP2 had its last activity in 2013, and the group has been dormant ever since.

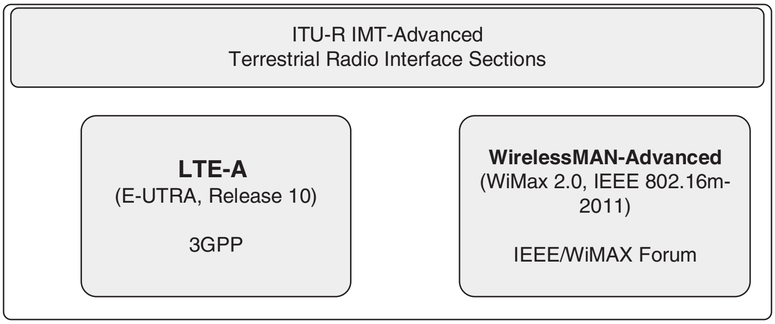

Figure 1.4 IMT-Advanced standards approved by ITR-R.

In October 2010, the ITU-R had completed the evaluation of six candidate submissions and approved two industry-developed technologies as the global 4G standards, as shown in Figure 1.4. Recommendation M.2012 [ITU-R M.2012, 2012] identifies the terrestrial radio interface technologies of IMT-Advanced and provides the detailed radio interface specifications.

1.5.1 Long-Term Evolution-Advanced (LTE-Advanced)

3GPP initiated the study item on LTE in late 2004, aiming at a disruptive radio-access technology dedicated to packet-switched data transmission. The study focused on technical requirements for LTE. The significant outcomes approved in June 2005 include low latency, high data rates at the cell edge, and spectrum flexibility. The 3GPP Radio Access Network (RAN) plenary meeting in December 2005 made a decision that the downlink of LTE should be based on Orthogonal Frequency-Division Multiple Access (OFDMA) and Single-Carrier Frequency-Division Multiple Access (SC-FDMA) in the uplink. In December 2008, the first release (Release 8) of the LTE air interface and its core network called the EPC was completed, followed by an enhanced version (Release 9) frozen in December 2009. LTE is a disruptive standard that was designed without the restriction of backward compatibility so that it is flexible to adopt new technical features. It can be operated in either FDD or TDD mode, referred to as LTE FDD and TD-LTE, respectively, with low latency and flat system architecture. The peak data rates reached 300 Mbps in the downlink and 75 Mbps in the uplink over a signal bandwidth of 20 MHz. In December 2009, TeliaSonera launched the world's first commercial LTE mobile services in the Scandinavian capitals Stockholm and Oslo, with network equipment provided by Ericsson and Huawei [Astely et al., 2009]. No LTE-compliant mobile phone was commercially available at that time, and the subscribers used computers with a USB wireless network adapter to access the LTE service. Until the September of 2010, Samsung SCH-r900, the world's first LTE-compliant mobile phone, was released.

Since LTE cannot fully comply with the requirements of IMT-Advanced, e.g. the peak data rate of 1 Gbps for low mobility and 100 Mbps for high mobility, 3GPP then continued to work on an enhanced version known as LTE-Advanced from 2009. The proposal based on LTE-Advanced was submitted to the ITU in October 2009, and more detailed specifications were completed later to form the first version of LTE-Advanced in Release 10. LTE-Advanced adopted significant technical features such as enhanced MIMO and a wider bandwidth up to 100 MHz to achieve high-speed transmission of 1 Gbps in the downlink and 500 Mbps in the uplink. In 2012, the Russian operator YOTA Networks announced the launch of the world's first LTE-Advanced network in Moscow using equipment from Huawei. Release 13 of the 3GPP specifications completed in early 2016 was the first version of *LTE-Advanced Pro*. The amount of new technical features was considered sufficient to merit a new LTE marker, but neither of *LTE-Advanced* and *LTE-Advanced Pro* implies a break of backward compatibility. As of this writing, 3GPP has completed Release 16 and is working on Release 17, which also includes further enhancements of LTE in addition to the specifications of fifth-generation (5G) [Dahlman et al., 2021].

The releases of the 3GPP specifications focusing on LTE are briefly summarized in the following paragraphs, as also shown in Figure 1.5.

- *Release 8* is the first definition of the LTE radio-access technology and the all-IP EPC network, forming the foundation for the following evolution. Spectrum

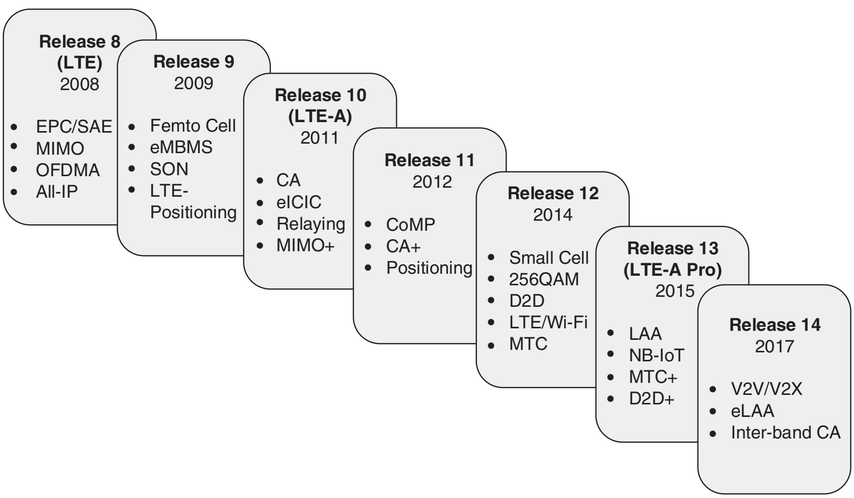

Figure 1.5 Releases of 3GPP specifications for LTE.

flexibility was emphasized by supporting paired and unpaired spectrum using FDD and TDD. It also supports flexible bandwidths (1.4, 3, 5, 10, 15, and 20 MHz) by scaling the number of OFDM subcarriers. Over a bandwidth of 20 MHz, the peak data rate can reach 150 Mbps in the uplink with 2×2 MIMO and 300 Mbps in the downlink with 4×4 MIMO.

- *Release 9* is the first evolution of LTE. It provided some improvements left behind from Release 8 and some minor enhancements, with the technical features including femtocell, MIMO beamforming, self-organized networks (SON), Enhanced Multimedia Broadcast Multicast Services (eMBMS), LTE positioning, and public warning system.
- *Release 10* specified the LTE-Advanced standard to ensure that the LTE radio-access technology can fully compliant with the IMT-Advanced requirements. It was frozen in March 2011 and introduced the technical features including carrier aggregation, enhanced uplink multiple access, MIMO enhancement, relaying, enhanced inter-cell interference coordination (eICIC), heterogeneous network deployment, and SON improvement.
- *Release 11* was finalized in September 2012, which further enhanced the performance and capabilities of LTE-Advanced. One of the most significant features of LTE Release 11 was the introduction of coordinated multi-point (CoMP) transmission and reception. Other improvements were carrier aggregation enhancement, a new control-channel structure, network-based positioning, RAN overload control for machine-type communication, and smartphone battery-saving technique.
- *Release 12* was completed in June 2014 and focused on the optimization and enhancements for small cells, including dual connectivity, dense small-cell deployment, small-cell on/off, and semi-dynamic TDD. Higher-order modulation (256QAM) was introduced to make use of high signal strength in small-cell environment. Another priority of this release was applying LTE technology for emergency events and public safety, with technical specifications for mission-critical application layer functional elements. Other features included device-to-device (D2D) communications, LTE TDD-FDD joint operation including Carrier Aggregation, Security Assurance Methodology, and LTE/WiFi integration.
- *Release 13* marked the start of LTE-Advanced Pro, which was sometimes in marketing dubbed 4.5G and seen as an intermediate step between the first release of LTE and the advent of 5G. Release 13 was a significant step, with many exciting features, such as license-assisted access (LAA) to support unlicensed spectra, improved support for machine-type communications, and further enhancements in MIMO, D2D communications, and carrier aggregation. Other efforts for expanding it to a set of new services and new verticals included the

introduction of narrow-band Internet of Things (NB-IoT) and the initial studies on Vehicle-to-Vehicle (V2V) communications.
- *Release 14* was frozen in 2017. Apart from enhancements to some of the features introduced in earlier releases, such as enhanced license-assisted access (eLAA) and inter-band carrier aggregation, it brought the support for V2V and Vehicle-to-Everything (V2X) communications, as well as wide-area broadcast with a reduced subcarrier spacing.

1.5.2 WirelessMAN-Advanced

As already mentioned, WiMAX Release 1.0 based on IEEE 802.16e-2005 802.16m was approved by the ITU in 2007 as the sixth global 3G standard under the name IMT-2000 OFDMA TDD WMAN. The subsequent step taken within the IEEE WMAN community was the development of IEEE 802.16m, aiming to extend the performance and capabilities of 802.16 radio-access technologies to ensure compliance with the IMT-Advanced requirements. In contrast to LTE-Advanced being a fully backward-compatible evolution of LTE, IEEE 802.16m was not a smooth evolution of IEEE 802.16e with some disruptive features [Dahlman et al., 2011]. Instead, IEEE 802.16m was recognized as a new standard although holding some essential characteristics of IEEE 802.16e, including the basic OFDM numerology. With time multiplexing, these two radio-access technologies can coexist on the same carrier within the IEEE 802.16e 5 ms frame structure. IEEE 802.16m adopted many features similar to LTE-Advanced, such as the use of carrier aggregation for bandwidths beyond 20 MHz and the support for relaying functionality. It also introduced much shorter subframes of length roughly 0.6 ms to reduce hybrid ARQ round-trip time and, in general, allow for reduced latency over the radio interface. Instead of inheriting the resource-mapping schemes defined for IEEE 802.16e, IEEE 802.16m introduced physical resource units consisting of a magnitude of frequency-contiguous subcarriers during one subframe, similar to the resource blocks in LTE. Each resource unit comprises 18 subcarriers with the subcarrier spacing of 10.94 kHz, resulting in a bandwidth close to the LTE resource-block bandwidth of 180 kHz. Due to many similarities between LTE-Advanced and IEEE 802.16m, it is not surprising that performance evaluations indicate the comparable performance of the two radio-interface technologies. Thus, similar to LTE-Advanced, IEEE 802.16m can also fulfill all the requirements for IMT-Advanced as defined by the ITU. In October 2010, WiMAX Release 2.0 based on IEEE 802.16m, along with LTE-Advanced, was approved by the ITU-R as one of the two IMT-Advanced standards under the name WirelessMAN-Advanced.

Table 1.4 Comparison of the main system parameters between LTE/LTE-Advanced and WiMAX.

Parameter	LTE	LTE-Advanced	WiMAX 1.0	WiMAX 2.0
Standard	3GPP Release 8	3GPP Release 10	IEEE 802.16e-2005	IEEE 802.16m-2011
Launch time	2009	2012	2006	2012
Bandwidth (MHz)	1.4, 3, 5, 10, 15, 20	(Aggregated) up to 100	1.25, 5, 10, 20	5, 10, 20, 40
Multi-access	DL: OFDMA	DL: OFDMA	DL: OFDMA	DL: OFDMA
	UL: SC-FDMA	UL: SC-FDMA	UL: OFDMA	UL: OFDMA
OFDM subcarrier	15 kHz	15 kHz	10.94 kHz	10.94 kHz
Duplex mode	FDD/TDD	FDD/TDD	TDD	TDD/FDD
Multi-Antenna	DL: 2x2,4x2,4x4	DL: up to 8x8	DL: 2x2	DL: up to 8x8
	UL: 1x2,1x4	UL: up to 4x4	UL: 2x1	UL: up to 4x4
Modulation	QPSK, 16QAM, 64QAM	Up to 256QAM[a)]	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Channel coding	Turbo codes	Turbo codes	Turbo codes/LDPC	Turbo codes/LDPC
Frame length	10 ms	10 ms	5 ms	5 ms
Mobility (km/h)	350	350	120	350
Data rate	DL: 300 Mbps	DL: 1 Gbps	DL: 75 Mbps	DL: 1 Gbps
	UL: 75 Mbps	UL: 500 Mbps	UL: 20 Mbps	UL: 200 Mbps
Latency	UP: 5 ms, CP: 50 ms	UP: 5 ms, CP: 50 ms	UP: 20 ms, CP: 50 ms	UP: 10 ms, CP: 30 ms

a) 3GPP Release 12 added the support of 256QAM in LTE-Advanced.
UP, user plane; CP, control plane.

WiMAX was pushed to the market much earlier than LTE and was a superior technology in terms of data throughput for a few years (2005–2009). Besides, it pioneered to adopt pre-4G technologies such as MIMO and OFDM and support new features such as variable transmission bandwidths. As early as 2006, two South Korean telecom operators launched the world's first mobile WiMAX service based on IEEE 802.16e standard under the brand of WiBro. As of October 2010, the WiMAX Forum claimed over 592 WiMAX (fixed and mobile) networks deployed in over 148 countries, covering over 621 million people. However, LTE was the evolution of dominant standards (i.e. GSM and WCDMA), whereas WiMAX was a relatively disruptive technology without a large user base. As a result, major mobile operators such as Verizon, Vodafone, China Mobile, NTT, and Deutsche Telekom chose to upgrade their legacy infrastructure from 3G to LTE smoothly rather than adopt a new technology standard. Ultimately, LTE/LTE-Advanced won the competition to become the dominant 4G standard. With LTE/LTE-Advanced, the world has thus converged into a universal global standard for mobile communications, deployed by essentially all mobile-network operators worldwide and applicable to both paired and unpaired spectra.

1.6 5G: From Human to Machine

5G was built on the success of 4G LTE and the exploration of 5G started before the full deployment of 4G. Some of the earliest efforts toward 5G technology commenced in the early 2010s, which demonstrated the feasibility of techniques that could be adopted. In August 2012, the New York University founded a multi-disciplinary academic research center known as NYU Wireless to develop the fundamental theories and pioneering work for 5G wireless communications. A key focus was on millimeter wave (mmWave) communications operating in the high frequency bands above 10 GHz. It got many research accomplishments such as the world's first radio channel measurements proving that the potential of mmWave spectrum and demonstrated the safety of mmWave radiation for the human body. Just two months later than the foundation of NYU Wireless, the University of Surrey in the United Kingdom announced to establish a new 5G research center jointly funded by the British government and a consortium of key mobile operators and vendors such as Huawei, Samsung, Telefonica, Fujitsu, and Rohde&Schwarz. In November 2012, a research project entitled *Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS)* funded by European Commission was kicked off [Osseiran et al., 2014]. METIS achieved an early global consensus on the picture of what would be 5G, prior to global standardization activities such as ITU-R and 3GPP.

Cellular Network for Human and Machine

In contrast to the previous generation cellular systems that focused merely on human-centric communication services, 5G needs to expand the sphere of mobile communications from human to things, from consumers to vertical industries, and from public to private networks. The potential scale of mobile subscription is substantially enlarged from merely billions of the world's population to almost countless inter-connectivity among humans, machines, and things. It enables a wide variety of disruptive use cases such as Industry 4.0, virtual reality, Internet of Things, and automatic driving.

In February 2013, the ITU-R Working Party 5D initiated two study items to analyze the IMT Vision for 2020 and future technology trends for the terrestrial IMT systems, known as IMT-2020. IMT-2020 was envisaged to support diverse usage scenarios and applications beyond the previous IMT systems. Furthermore, a broad variety of capabilities would be tightly coupled with these intended different usage scenarios and applications, as shown in Figure 1.6. Part of the study outcomes was transferred to ITU-R Recommendation M.2083 released in 2015 [ITU-R M.2083, 2015], where three usage scenarios were firstly defined:

- *enhanced Mobile Broadband (eMBB):* Mobile broadband addresses the human-centric use cases for access to multi-media content, services, cloud, and data. With the proliferation of smart devices (smartphones, tablets, and wearable electronics) and the rising demand for video streaming, the need for mobile broadband continues to grow, setting new requirements for what ITU-R calls eMBB.

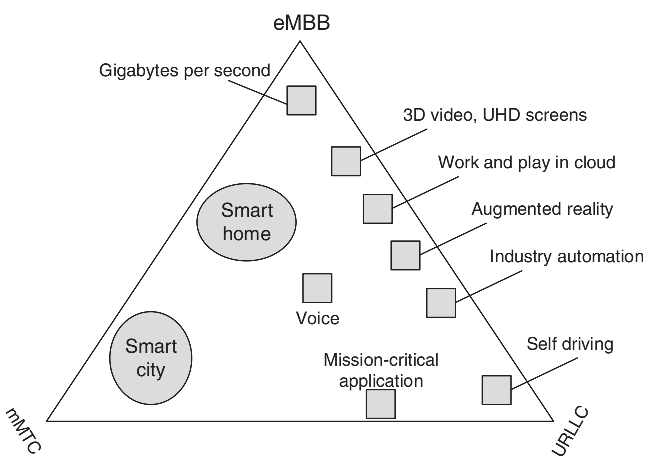

Figure 1.6 Usage scenarios of IMT-2020 defined in ITU-R M.2083. Source: Adapted from ITU-R M.2083 [2015].

This usage scenario comes with new use cases and requirements for improved capabilities and an increasingly seamless user experience. eMBB covers various cases, including wide-area coverage and hot spots, which have different requirements. For the hot-spot case, i.e. for an area with high user density, very high traffic capacity is needed, while the requirement for mobility is low and user data rate is higher than that of wide-area coverage. Seamless coverage and medium to high mobility are desired for the wide-area coverage case, with a substantially improved data rate than existing data rates. However, the data rate requirement may be relaxed compared with hot spots.

- *Ultra-Reliable Low-Latency Communications (URLLC):* This scenario aims to support both human-centric and critical machine-type communications. It is a disruptive promotion over the previous generations of cellular systems that focused merely on the services for mobile subscribers. It opens the possibility for offering mission-critical wireless applications such as automatic driving, vehicle-to-vehicle communication involving safety, wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, and transportation safety. It is characterized by stringent requirements such as ultra-low latency, ultra-reliability, and availability.
- *massive Machine-Type Communications (mMTC):* This scenario supports massive connectivity with a vast number of connected devices that typically have very sparse transmissions of delay-tolerant data. Such devices, e.g. remote sensors, actuators, and monitoring equipment, are required to be low cost and low power consumption, allowing for a very long battery life of up to 10 years due to the possibility of remote Internet of Things (IoT) deployment.

IMT-2020 was expected to provide far more enhanced capabilities than those of IMT-Advanced. In addition, IMT-2000 can be considered from multiple perspectives, including the users, manufacturers, application developers, network operators, and service and content providers. Therefore, it is recognized that technologies for IMT-2020 can be applied in a variety of deployment scenarios and can support a range of environments, service capabilities, and technology options [Andrews et al., 2014]. Based on the usage scenarios and applications described as Recommendation M.2083, the ITU-R defined a set of technical performance requirements. In November 2017, ITU released Recommendation M.2410 *Minimum requirements related to technical performance for IMT-2020 radio interface* [ITU-R M.2410, 2017], as the baseline for the evaluation of IMT-2020 candidate technologies. In addition to the peak data rates of 20 Gbps in the downlink and 10 Gbps in the uplink following the tradition of offering higher transmission rates, a number of novel Key Performance Indicators (KPIs) such as reliability, energy efficiency, and connection density were set up. The key

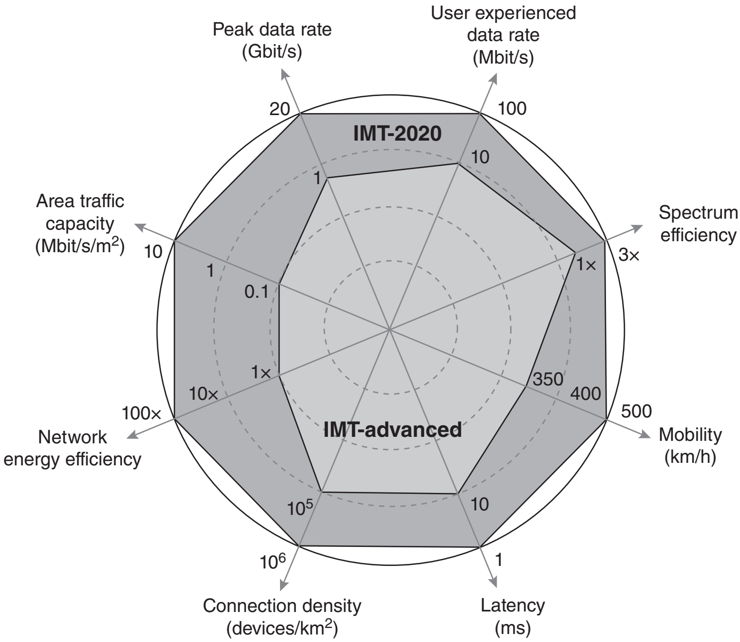

Figure 1.7 Improvement of key performance indicators from IMT-Advanced to IMT-2020. Source: ITU-R M.2083 [2015]/ITU.

capabilities of IMT-2020 are shown in Figure 1.7, compared with those of IMT Advanced. Table 1.5 provides a summary of these performance requirements.

Another milestone for 5G development was the identification of its spectrum discussed in the World Radio Conference. At WRC-15, a new set of frequency bands below 6 GHz (e.g. 470–694, 694–790, and 3300–3400 MHz) were identified for IMT on a global basis. This conference also appointed an agenda item for the following WRC-19 toward the identification of higher spectrum above 24 GHz for IMT-2020 mobile services. Based on the studies conducted by the ITU-R after WRC-15, WRC-19 noted that the ultra-low latency and very-high data-rate applications require larger contiguous blocks of spectrum. As a consequence, a total of 13.5 GHz spectrum consisting of a set of high-frequency bands were assigned for the deployment of 5G mmWave communications:

- 24.25–27.5 GHz
- 37–43.5 GHz
- 45.5–47 GHz
- 47.2–48.2 GHz
- 66–71 GHz

Table 1.5 Minimum technical performance requirements for IMT-2020.

KPI	Minimum performance requirement
Peak data rate	Downlink: 20 Gbps
	Uplink: 10 Gbps
Peak spectral efficiency	Downlink: 30 bps/Hz
	Uplink: 15 bps/Hz
User-experienced rate	Downlink: 100 Mbps
	Uplink: 50 Mbps
5th-percentile user	Downlink: 0.12–0.3 bps/Hz
Spectral efficiency	Uplink: 0.045–0.21 bps/Hz
Average spectral efficiency	Downlink: 3.3–9 bps/Hz
	Uplink: 1.6–6.75 bps/Hz
Area traffic capacity	10 Mbps/m ^{2} (indoor hot spot)
User plane latency	4 ms – eMBB
	1 ms – URLLC
Control plane latency	20 ms
Connection density	1 000 000 devices per km ^{2}
Energy efficiency	The support for two aspects:
	(1) Efficient data transmission in a loaded case
	(2) Low energy consumption when there is no data
Reliability	1–10 $^{-5}$ (99.999%)
Mobility	up to 500 km/h
Mobility interruption time	0 ms
Maximal bandwidth	100 MHz for sub-6 GHz
	1 GHz for mmWave

With the IMT-2020 framework defined by the ITU-R and the frequency bands identified by the WRC, the task of specifying detailed technologies fell into the standardization bodies. Unlike conflicting technical paths and multiple standardization authorities in the previous generations, 3GPP played a dominant role during the development of 5G technologies. Its technical specifications that were organized as releases acted actually as *de facto* standards. As early as 2015, 3GPP RAN group decided to set up a study item in Release 14 for 5G New Radio (NR) and initiated the task on channel modeling for frequency bands above 6 GHz. The specification of the initial 5G NR was carried out through a work item in Release 15. To meet commercial requirements on early large-scale trials and deployments in 2018, earlier than the initially envisaged timeline of around 2020, 3GPP committed to accelerating the process, agreeing that a Non-Standalone (NSA) variant would be finalized earlier. At the end of 2017, the first version of 5G specifications was available. In such an NSA deployment, the NR air interface is connected to the existing EPC core network, making the capacities offered by the NR (lower latency, etc.) available without network replacement. The world's first 5G NSA call was jointly completed in Spain by Vodafone and Huawei, just ahead of Mobile World Congress, which started on 26 February 2018. After the initial delivery of NSA, much effort of 3GPP was shifted on timely completion of Release 15 to form the first complete set of 5G standards. Therefore, 3GPP also developed a new core network referred to as the 5G Core (5GC) network in parallel to the NR radio-access technology. In June 2018, the final version of Release 15 that can support the Standalone (SA) operation of 5G NR was available, marking the completion of 5G Phase 1.

The focus of Release 15 was primarily on eMBB and (to some extent) URLLC, while mMTC was still supported by using LTE-based machine-type communication technologies such as eMTC and NB-IoT. Release 15 provided the foundation on which 3GPP continues its work to evolve the capability and functionality of 5G so as to support new spectrum and new applications, and further enhance existing core features. The evolution of 5G NR continued in Release 16, often referred to informally as "5G Phase 2", which was completed in June 2020. Technical features were added into 5G NR for the support of Industrial Internet of Things (IIoT) and the enhancement of URLLC applications. This release aimed to meet the IMT-2020 requirements and, along with Release 15, acted as the initial complete 3GPP 5G specifications submitted to the ITU-R. The 3GPP final proposal included two separate and independent submissions, defined as the single Radio Interface Technology (RIT) and the combined Sets of Radio Interface Technologies (SRIT). In November 2020, the ITU-R announced that 3GPP 5G-SRIT and 3GPP 5G-RIT conform with the IMT-2020 vision and stringent performance requirements. As of this writing, 3GPP works on Release 17, the third version of 5G, with a rolling schedule of completing Stage 2 in 2021 and stage 3 in 2022. Release 17 is probably the most versatile release in the history of 3GPP in terms of the number of technical features, as shown in Figure 1.8. 3GPP also announced its evolution of 5G toward 5.5G with the official new name of *5G-Advanced*, which will be standardized in Release 18 and beyond.

In April 2019, when South Korea's three mobile operators – SK Telecom, LG U+, and KT – and US Verizon were arguing with each other about who is the world's first provider of the 5G communication services, we stepped into the era of 5G. In the past two years, we have witnessed a strong expansion of 5G networks across the world and a great growth of 5G subscriptions in major countries. At the end of 2020, for instance, the penetration rate of 5G usage in South Korea

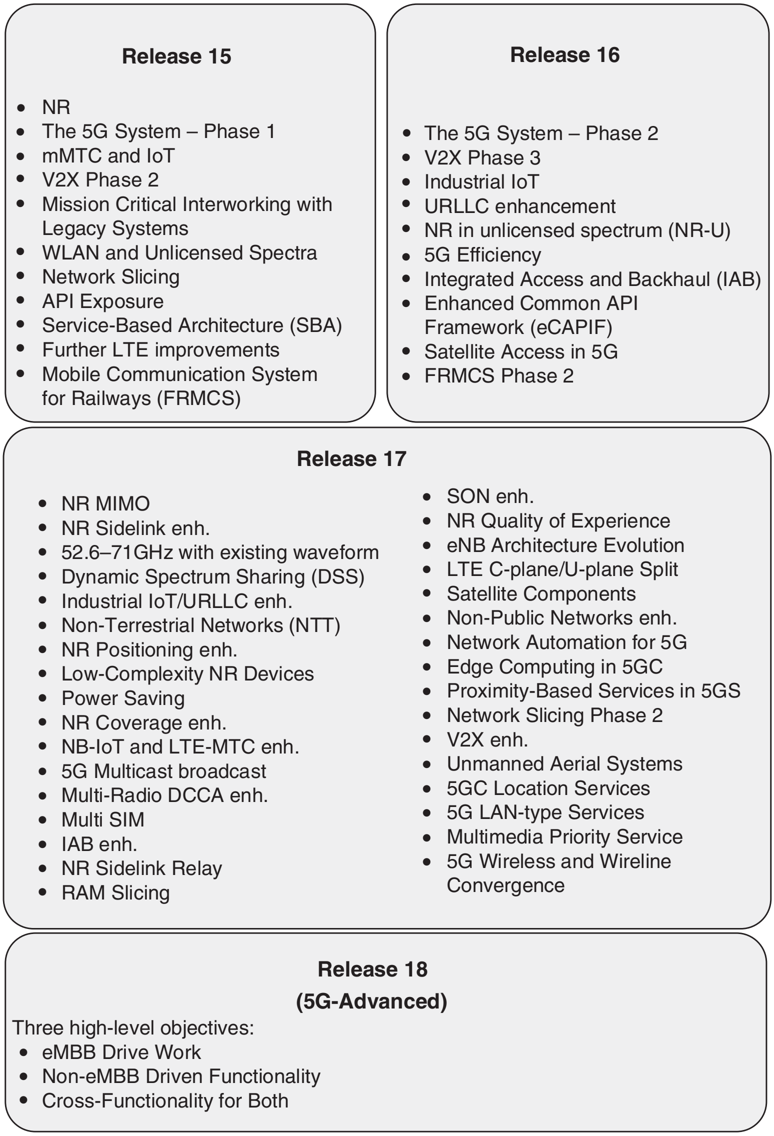

Figure 1.8 Releases of the 3GPP NR-5GC specifications.

had surpassed 15.5% while China had deployed more than 700 000 base stations to serve around 200 million 5G subscribers. Meanwhile, the term *5G* has been remaining one of the hottest buzzwords in the media, attracting unprecedented attention from the whole society. It even went beyond the sphere of technology and economy, becoming the focal point of geopolitical tension. When we start the writing of this book, more than 400 mobile operators in approximately 130 countries are investing in 5G networks and the number of 5G subscribers already reaches a very large scale in many regions. In 2020, the outbreak of the COVID-19 pandemic leads to a dramatic loss of human life worldwide and imposes unprecedented challenges on societal and economic activities. But this public health crisis highlights the unique role of networks and digital infrastructure in keeping society running and families connected, especially the values of 5G services and applications, such as remote surgeon, online education, remote working, driver-less vehicles, unmanned delivery, robots, smart healthcare, and autonomous manufacturing.

1.7 Beyond 5G

Currently, 5G is still on its way being deployed across the world, but it is already the time for academia and industry to shift their attention to beyond 5G or the sixth generation (6G) systems, in order to satisfy the future demands for information and communications technology (ICT) in 2030 (Figure 1.9). Even though discussions are ongoing within the wireless community as to whether there is any need for 6G or whether counting the generations should be stopped at 5, and even there is an opposition to talking about 6G [Fitzek and Seeling, 2020], several pioneering works on the next-generation wireless networks have been initiated [Jiang and Schotten, 2021]. A focus group called *Technologies for Network 2030* within the International Telecommunication Union Telecommunication (ITU-T) standardization sector was established in July 2018. The group intends to study the capabilities of networks for 2030 and beyond [ITU-T NET-2030, 2019], when it is expected to support novel forward-looking scenarios, such as holographic-type communications, ubiquitous intelligence, Tactile Internet, multi-sense experience, and digital twin. The European Commission initiated to sponsor beyond 5G research activities, as its recent Horizon 2020 calls – ICT-20 *5G Long Term Evolution* and ICT-52 *Smart Connectivity beyond 5G* – where a batch of pioneer research projects for key 6G technologies were kicked off at the early beginning of 2020. The European Commission has also announced its strategy to accelerate investments in Europe's "Gigabit Connectivity" including 5G and 6G to shape Europe's digital future [EU Gigabit Connectivity, 2020]. In October 2020, the Next Generation Mobile Networks (NGMN) has launched its new "6G Vision and Drivers" project, intending to provide early and timely direction for global 6G activities. At its meeting in February 2020, the ITU-R sector decided to start study on future technology trends for the future evolution of International Mobile Telecommunications (IMT) [ITU-R WP5D, 2020]. In Finland, the University

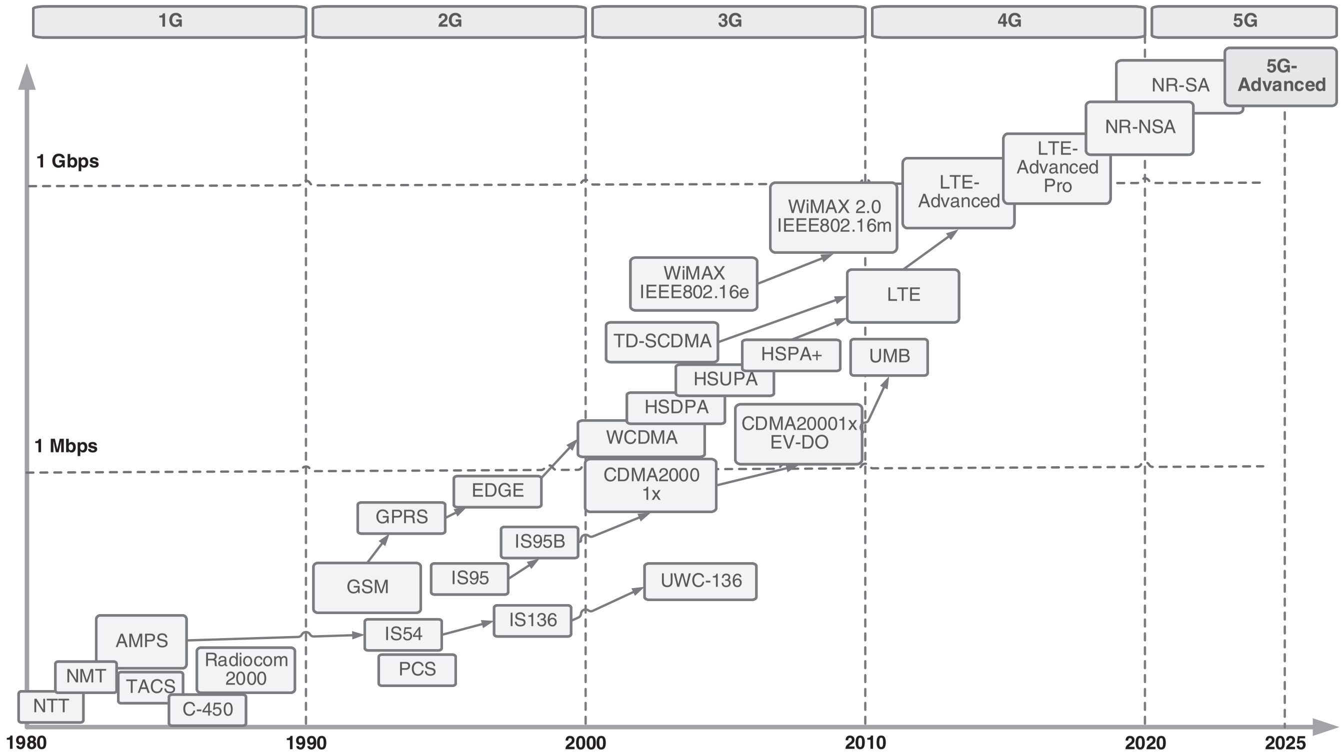

Figure 1.9 The evolution of cellular systems.

of Oulu began ground-breaking 6G research as part of Academy of Finland's flagship program [Latva-aho et al., 2019] called 6G-Enabled Wireless Smart Society and Ecosystem (6Genesis), which focuses on several challenging research areas including reliable near-instant unlimited wireless connectivity, distributed computing and intelligence, as well as materials and antennas to be utilized in future for circuits and devices. Besides, other traditional main players in mobile communications, such as the United States, China, Germany, Japan, and South Korea, already initiated their 6G research officially or at least announced their ambitions and tentative roadmap [Jiang et al., 2021].

1.8 Conclusions

As the starting point of this book, this chapter reviewed the evolution of mobile systems from the pre-cellular systems to the latest 5G cellular networks. The content was organized in terms of the generation of mobile systems. Each section dedicates to one generation of cellular systems, where the main content generally consists of three main parts: (i) The underlying motivation of evolution; (ii) The milestones of development and deployment; and (iii) Comparative review of different technical standards. The purpose of this chapter is to provide the reader an overall view of all previous generations and the evolution path, so that they can well understand the state-of-the-art advances for the upcoming 6G system. Next chapter we will provide an in-depth introduction of the previous generations consisting of their system architecture and key technologies.

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