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Historical Sketch of Cellular Communications and Networks

Cellular communication and network systems have changed rapidly over the past four decades and have adopted new technologies. The cellular communication and network industry has evolved from the first generation (1G) to the fifth generation (5G). The term "generation" is based on the 3GPP standard group's releases. In this chapter, we look into the evolution of cellular communications and networks in terms of technology enhancement, cost reduction, and use case expansion.

1.1 Evolution of Cellular Communications and Networks

Mobile phones have now become essential devices to people in their day-to-day lives. Their history began in the early 1900s. The predecessors of cellular systems were actually two-way radio systems for ships and trains. In 1906, a Canadian-born inventor Reginald Fessenden made the first two-way voice transmission using amplitude modulation. In 1926, the German National Railway (Deutsche Reichsbahn) provided first-class passengers with mobile telephony services on the train route between Berlin and Hamburg. After World War II, the developments for portable-size devices accelerated in many countries. At this stage, the mobile devices were not based on a cellular concept and did not need base stations. They supported only a few users and were very expensive. Thus, those mobile devices are regarded as the "zero generation" (0G).

In 1973, Martin Cooper and John F. Mitchell of Motorola demonstrated the first public mobile phone call using a device weighing 1.1 kg [1]. In 1979, Nippon Telegraph and Telephone (NTT) deployed the first commercial cellular network in Tokyo, Japan. In 1981, the Nordic Mobile Telephone (NMT) group launched the first mobile phone network supporting international roaming among Finland, Sweden, Norway, and Denmark. Two types of NMT are NMT-450 (450 MHz frequency bands) and NMT-900 (900 MHz frequency bands). NMT-900 had more channels than NMT-450. In 1983, Advanced Mobile Phone Service (AMPS) was launched in Chicago, USA, using the Motorola DynaTAC 8000x mobile phone. The DynaTAC was the pocket-sized phone supporting about 30 minutes talk time. It was a significant improvement and heralded a new era of cellular phones. This was the first generation (1G) cellular system supporting voice calls and using analogue technology. The technical specifications of 1G systems are summarized in Table 1.1.

Design and Optimization for 5G Wireless Communications, First Edition. Haesik Kim.

Table 1.1 Technical specifications of 1G cellular systems.

	NMT (NMT-450 and NMT-900)	AMPS
Frequency band (MHz)	463 to 468 (Rx) and 453 to 458 (Tx) in NMT-450 standard, 935 to 960 (Rx) and 890 to 915 (Tx) in NMT-900 standard	824 to 849(Tx) and 869 to 894 (Rx)
Channel bandwidth	25 kHz in NMT-450 standard, 12.5 kHz in NMT-900 standard	30 kHz
Multiple access scheme	FDMA	FDMA
Duplex scheme	FDD	FDD
No. of channels	200 in NMT-450 and 1999 in NMT-900	832 in AMPS and 2496 in Narrow band AMPS
Modulation	Frequency modulation (FM)	Frequency modulation (FM)
Number of users per channel	One	One
Base station antenna	Omni-directional	Omni-directional
Switch type	Circuit switching	Circuit switching
Data rate	2.4 ~ 14.4 kbps	2.4 ~ 14.4 kbps

The 1G analogue system established the foundation of cellular networks and adopted key techniques such as frequency reuse, licensed spectrum and coordinated mobile network. The cellular concept [2] allows us to overcome many problems such as coverage, power consumption, user capacity, interference, and so on. The frequency reuse is a key idea of the cellular concept. Neighboring cells operate on different frequencies. Thus, the interference can be reduced and cell capacity can be increased. In addition, the mobile operator holds licensed spectrum for exclusive use and coordinates the call for seamless access. However, the 1G analogue system had the limitation of capacity because the frequency division multiple access (FDMA) system is inefficient. The FDMA of 1G systems supports only one user per channel. The 1G device was heavy, with a high energy consumption, and high cost.

In 1991, the second generation (2G) of cellular systems was commercially launched in Finland. The 2G systems can be divided into the global system for mobile communications (GSM) using time division multiple access (TDMA) technology, and IS-95 (or cdmaOne) using code-division multiple access (CDMA) technology. GSM is very widely deployed in all countries. About 80% of all 2G subscribers around the world used GSM [3]. IS-95 is deployed in the US and parts of Asia. About 17% of all 2G subscribers around the world used IS-95 [3]. In addition, TDMA-based IS-136 was developed as an AMPS evolution in the US but migrated to GSM. The 2G digital systems are voice-oriented systems supporting voice-mail and short messaging service (SMS). The GSM is based on a TDMA technique that support eight users per 200 kHz frequency band by assigning different time slots for

Table 1.2 Technical specifications of 2G cellular systems.

	GSM	**IS-95**
Frequency bands	850/900 MHz, 1.8/1.9 GHz	850 MHz/1.9 GHz
Channel bandwidth	200 kHz	1.25 MHz
Multiple access scheme	TDMA/FDMA	CDMA
Duplex scheme	FDD	FDD
Frame duration	20 ms	4.6 ms
Modulation	GMSK	BPSK
Modulation efficiency (bps/Hz)	1	1.35
Spectrum efficiency (conversation/cell/MHz)	12.1 ~ 45.1	5.0 ~ 6.6
Switch type	Circuit switching for voice and packet switching for data	Circuit switching for voice and packet switching for data

each user. As a modulation technique of the GSM system, Gaussian minimum shift keying (GMSK) is adopted. It allows the GSM system to have a constant envelope property, providing low power consumption. The technical specifications for 2G systems are summarized in Table 1.2.

The main disadvantages of the 1G systems were low capacity, high-energy consumption, and heavy and high-cost handsets. In 2G systems, the capacity problem was solved by voice compressing techniques and TDMA/CDMA techniques. The high energy consumption problem was solved by the lower radio power emission of the digital system. The heavy and high-cost handset problem was solved by low digital component cost and size. In addition, simple encryption was used in 2G systems. However, the 2G system still requires a large frequency spacing to reduce interference and does not support soft-handover. Most importantly, there were market requirements relating to data services such as real-time news, stock information, weather, location, and so on. The 2G system could not satisfy them and evolved to 2.5G systems. Thus, the general packet radio services (GPRS) appeared in the market and allowed limited web browsing and multimedia services such as wireless application protocol (WAP), multimedia messaging services (MMS), and email access. The main difference between 2G systems and 2.5G systems is the switching method. The 2G systems are designed for voice services in a circuit-switched network. However, the 2.5G systems are designed to support data services so it partially implements a packet-switched network. The reason why we call this system 2.5G is that it was not a major change but an upgrade over existing 2G infrastructure. It required some modification of base stations and mobile phones. Besides GPRS, there were Enhanced Data rates for GSM Evolution (EDGE) and high-speed circuit-switched data (HSCSD) as an evolution of TDMA systems, and IS-95B as an evolution of CDMA systems. However, the 2.5G systems were not deployed widely due to the following limitations:

(i) The actual data rate was much lower than advertised. The maximum data rate of 172.2 kbps could be achieved when a single user takes all radio resources (8 time-slots) without any error protection. However, a mobile operator should provide a subscriber with enough radio resources. Thus, the actual data rate was about 30–40 kbps.
(ii) Transit delays occurred. The GPRS data packets arrived at one destination from many different places. It caused packet loss or corruption over the radio links.
(iii) Applications were limited. It supported many applications such as email, internet access, location-based services, and so on. Traditional web browsers support access to full websites with high-resolution images, video, and lots of information. However, WAP scaled this down and supported a small-size image and text-based website. It did not meet the market requirement, and thus many mobile operators waited for the next generation (3G).

NTT Docomo launched the first pre-commercial 3G network in 1998, and then deployed the first commercial 3G network based on W-CDMA technology in Japan in October 2001. SK Telecom commercially launched the first 3G network based on CDMA200 technology in South Korea in January 2002. 3G systems provide us with much higher data rates, better voice quality and multimedia services. In order to achieve a global interoperability of mobile networks, the International Telecommunication Union (ITU) identified a global frequency band in the 2 GHz range and invited proposals for IMT-2000 to meet high data rate requirements: 2 Mbps for fixed users, 284 kbps for pedestrians, and 144 kbps for vehicular environments. The 3G services include global roaming, high-quality voice calls, location-based services, video conferencing, video on demand, online banking and so on. The ITU approved several proposals for IMT-2000. Two major proposals were the Universal Mobile Telecommunications Service (UMTS), also called W-CDMA, by the Third Generation Partnership Project (3GPP) standard (GSM camp), and the CDMA2000 by the 3GPP2 standard (IS-95 camp). They both selected CDMA as the multiple access technique because of multiple benefits: (i) more efficient spectrum use; (ii) increased system capacity; and (iii) better security. There are many similarities between the two systems: direct sequence spreading spectrum (DSSS) multiple access, orthogonal code channelization, random access, power control scheme, rake receivers, soft handover, voice decoder, and so on. The technical specifications of 3G systems are summarized in Table 1.3.

The UMTS was originally developed by the European Telecommunications Standard Institute (ETSI). However, the seven telecommunications standard development organizations (ETSI, ARIB, ATIS, CCSA, TSDSI, TTA, and TTC) built a partnership known as the 3GPP, and the 3GPP completed the UMTS standards as the evolution of GSM in 1999. The UMTS architecture supporting backward compatibility with GSM and GPRS architecture is composed of (i) a core network (CN) with functions of switching, routing, and subscriber management, (ii) UMTS Terrestrial Radio Access Network (UTRAN) connecting mobile phones to the public switched telephone network (PSTN) and packet networks, and (iii) user equipment (UE) such as mobile phones and any handheld devices. The CDMA2000 1× implies the same bandwidth (1.25 MHz) as the 2G (IS-95). The data rate of CDMA2000 1× has been increased but it could not meet the 3G requirements of the ITU. Thus, it was

Table 1.3 Technical specifications of 3G cellular systems.

	UMTS (3 GPP Release 99)	CDMA2000 (1x)
Frequency bands	850/900 MHz, 1.8/1.9/2.1 GHz	450/850 MHz 1.7/1.9/2.1 GHz
Channel bandwidth	5 MHz	1.25 MHz
Multiple access scheme	CDMA	CDMA
Duplex scheme	FDD/TDD	FDD
Data modulation	DSSS, QPSK	DSSS, BPSK/QPSK
Peak data rate	384~2048 kbps	307 kbps
Chip rate	3.84 Mcps	1.2288 Mcps
Frame length	5 ms (signaling), 20, 40, 80 ms physical layer frames	10 ms for physical layer, 10, 20, 40, and 80 ms for transport layer
Channel coding	Convolutional and turbo code	Convolutional and turbo code
Network synchronization	Synchronous/asynchronous	Synchronous
Core network	GSM-MAP	ANSI-41

evolved to CDMA200 EV-DO (Evolution, Data Only) in October 2000. As the name EV-DO implies, it supports data only. It provides up to 2.4 Mbps downlink data rate and up to 153 kbs uplink data rate, and includes new techniques such as adaptive coding and modulation, data optimized channel, and opportunistic scheduling. In the late 1990s, the data usage pattern was asymmetric. The higher data rates are required in downlink to access the internet, download a huge file and use video-on-demand services. In order to respond to market demands for much higher data rates, the next evolution is high-speed packet access (HSPA) as 3.5G systems by the 3GPP. In the HSPA family, high-speed downlink packet access (HSDPA) was introduced in 3GPP Release 5 in 2002. The HSDPA supported up to 14.4 Mbps peak data rate theoretically, but the typical user data rate was 500 kbps to 2 Mbps. The HSDPA adopted new advanced techniques (hybrid automatic repeat request [HARQ], link adaptation, fast dynamic scheduling) to deliver higher data rates and more capacity [4]. The HARQ improved the performance by reducing the retransmission rate. There are two types of HARQ: chase combining HARQ, and Incremental redundancy HARQ. The chase combining HARQ is regards as repetition coding. The retransmission includes the same information and redundancy. The receiver combines the received bits with the same bits from the previous transmission using maximum ratio combining (MRC). In contrast, the incremental redundancy HARQ uses multiple different sets of coded bits. They are transmitted in different channels and the receiver obtains additional information. Link adaptation techniques help to increase system throughput. The UE of HSDPA reports a channel quality indicator (CQI) to a base station (NodeB). Depending on this channel state information, the base station varies the modulation order and coding rate per user and frame. The fast dynamic scheduler provides us with better radio resource utilization by exploiting the diversity of channels and allocating more radio resource to a user whose channel condition is favorable. High-speed uplink packet access (HSUPA) was introduced in 3GPP Release 6 in 2004. The HSUPA supports up to 5.76 Mbps peak data rate theoretically, but a typical user data rate was 500 kbps to 1 Mbps. This high data rate allows us to use more applications such as Voice over Internet Protocol (VoIP). The HSUPA added the enhance dedicated channel (E-DCH) to UMTS and included new features such as a shorter transmission time interval (TTI). After that, evolved HSPA (HSPA+) was introduced in 3GPP Release 7. It provides us with high data rates (up to 42.2 Mbps in downlink and up to 22 Mbps in the uplink) and includes new techniques (high order modulation, 2×2 multiple input multiple output [MIMO]). The high order modulation such as 64QAM allows us to improve by about 50% more data transmission in the packets. The MIMO plays a key role in HSPA and beyond. About 25% average cell throughput gain is achieved by a HSPA+MIMO solution when compared with a single antenna system [5].

The driving force for 4G systems comes from market needs. Although 3G systems improved significantly over 2G systems, the main function was still voice communications on circuit switch systems. People preferred to use broadband data services offered by wired communication systems (ADSL, cable modem, and so on) and short-range wireless communication systems (WiFi) because the mobile data service by cellular systems was much more expensive than ADSL and WiFi. Thus, 4G systems were developed on a new network architecture. Voice services and data services are no longer separated. All IP core networks of 4G systems support both voice service and high-speed data services including multimedia services, mobile TV, video conferencing, and so on. Another driving force is popularization of the smartphone. Unlike a traditional cellular phone, smartphones have a full keyboard, large display, touch screen, cameras, video recorder, GPS navigation, microphones, and many sensors (accelerometer, gyroscope, magnetometer, light sensor, proximity sensor, barometer, thermometer, fingerprint sensor, etc.). Smartphones are powerful mobile devices as much as a laptop. Thus, data services became more important than voice services. In 2008, ITU defined requirements of IMT-Advanced (4G systems) including 100 Mbps for vehicular environments and 1 Gbps for fixed users or pedestrians. However, two major proposals, mobile WiMAX and LTE, known as 4G systems, do not fulfill the requirements of IMT-Advanced. Nevertheless, they were approved as 4G systems. After that, both systems gradually improved and met many parts of the requirements. In terms of technology, they both have many similarities such as all IP networks, orthogonal frequency division multiple access (OFDMA) based multiple access schemes, MIMOs, and so on. On the other hand, the differences are (i) compatibility: LTE is compatible with 3G, but WiMAX does not support coexistence of WiMAX and 3G; (ii) mobility support: LTE supports up to 450 km/h, but WiMAX supports up to 120 km/h; (iii) frame duration: LTE has 10 ms frame duration but WiMAX frame duration is 5 ms; (iv) channel bandwidth: LTE channel bandwidth is from 1.4 to 20 MHz but WiMAX uses from 5 to 10 MHz; and so on. The technical specifications of 4G systems are summarized in Table 1.4.

Table 1.4 Technical specifications of 4G cellular systems.

	LTE (3 GPP Release 8)	Mobile WiMAX (IEEE 802.16e-2005)
Frequency bands	700 MHz, 1.7/2.1 GHz, 2.6 GHz, 1.5 GHz	2.3 GHz, 2.6 GHz, and 3.5 GHz
Channel bandwidth	Scalable, 1.4, 3, 5, 10, 15, 20 MHz	Scalable, 5, 7, 8.75, 10 MHz
Data rate	150 Mbps (DL)/75 Mbps (UL)	46 Mbps(DL)/7 Mbps (UL)
Frame size	1 ms (sub-frame)	5 ms (frame)
Multiple access scheme	OFDMA (DL)/SC-FDMA (UL)	OFDMA
Duplex scheme	FDD/TDD	FDD/TDD
FFT size	128, 256, 512, 1024, 1536, 2048	128, 512, 1024, 2048
OFDMA symbol duration	71.8, 71.3, 83.2, and 166.6 μs	102.9 μs
Cyclic prefix	1/4, 1/8, 1/16 and 1/32	Normal, Extended
Modulation	QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Subcarrier spacing	7.5, 15 kHz	10.9375 kHz
Channel coding	Convolutional coding, Convolutional turbo coding	Convolutional coding, Convolutional turbo coding
MIMO	Multilayer precoded spatial multiplexing, space frequency block coding	Beamforming, space time coding and spatial multiplexing
Networks	All IP EUTRAN network, two-tier architecture (EUTRAN and EPC)	All IP network, two-tier architecture (ASN and CSN)

1.2 Evolution to 5G Networks

The 3GPP continuously evolves for more data capacity. Capacity of cellular systems has been improved by three different approaches: bandwidth increase, spectral efficiency increase, and frequency reuse. According to Shannon's capacity formula [6] and extended capacity for MIMO channels [7], channel capacity can be simply expressed as follows:

$$C = W \cdot n \cdot \log_2(1 + S/N) \tag{1.1}$$

where C, W, n, S/N are channel capacity, bandwidth, number of antennae and signal-to-noise ratio, respectively. The first approach (bandwidth increase) is to increase W

by more bandwidth by regulation, carrier aggregation technique, and cognitive radio. The second approach (spectral efficiency increase) is to increase n by MIMO techniques and S/N by interference mitigation techniques, error correction coding, traffic adaptation, and so on. The third approach (frequency reuse) is to increase the number of cells or sections by cell sectorization and femto cells. The channel capacity in Equation (1.1) can be modified as follows:

$$C = W \cdot n \cdot \sum \log_2(1 + S/N) \tag{1.2}$$

Based on those approaches, cellular systems improved system capacity significantly. Now, we prepare for the 5G era and expect life enhancement, such as can be achieved by new features of 5G systems such as the Internet of Things (IoT), public safety, proximity service, vehicular communications, terrestrial TV, Gbps mobility, and so on. In order to achieve the goals for 5G, the standard bodies set high requirements, and industry and academia stay in line with them. From 1G to 4G, the main target metric was system capacity. However, 5G systems focus not only on system capacity but also latency, connection density and energy efficiency. The 5G applications can be classified into three main communication applications: (i) enhanced mobile broadband communication (eMBB); (ii) ultra-reliable and low latency communication (URLLC), and (iii) massive machine type communication (mMTC). The ITU defined 5G as IMT-2020 in 2015. The ITU's Radiocommunication Sector (ITU-R) Working Party 5D has the leading role and plans to deploy the 5G system in 2020 [8]. The 3GPP also plans to enhance the LTE system and meet the 5G requirements of ITU [9]. The 5G target of the 3GPP is to (i) improve LTE capacity and performance, and (ii) address a new business segment. The 3GPP standards keep expanding their platform to new 5G services while improving their system performance to meet ambitious 5G requirements. The initial features were completed in September 2016 and the broader framework was finalized in June 2017 (Release 14).

As we can observe in Figure 1.1, 3GPP 5G Phase 1/Release 15 is planned to complete in September 2018. Key features of Release 15 will be forward compatibility with previous versions, eMBB, roaming, charging, network sharing, QoS control, and so on. 3GPP 5G Phase 2/Release 16 is planned to complete in March 2020. Key features of Release 16 will be compatibility with non-3GPP access, IoT, satellite support, URLLC, 5G media for virtual reality, and so on. Cellular systems have evolved approximately every 20 years, as shown in Figure 1.2. We expect 5G to revolutionize our day-to-day life and various industries (telecommunications, transportation, public safety, healthcare, manufacturing, media, etc.) in the near future. In [10], ITU-R summarizes 5G use cases and applications: transportation,

	Sept 2016	Dec 2016	Mar 2017	Jun 2017	Sept 2017	Dec 2017	Mar 2018	Jun 2018	Sept 2018	Dec 2018	Mar 2019	Jun 2019	Sept 2019	Dec 2019	Mar 2020
R14				Complete											
R15				Stage 1		Stage 2		Stage 3	Complete						
R16										Stage 1		Stage 2		Stage 3	Complete

5G Phase 1 (Sept 2016 – Dec 2018)

5G Phase 2 (Jun 2017 – Mar 2020)

Figure 1.1 Timeline of 3GPP 5G developments.

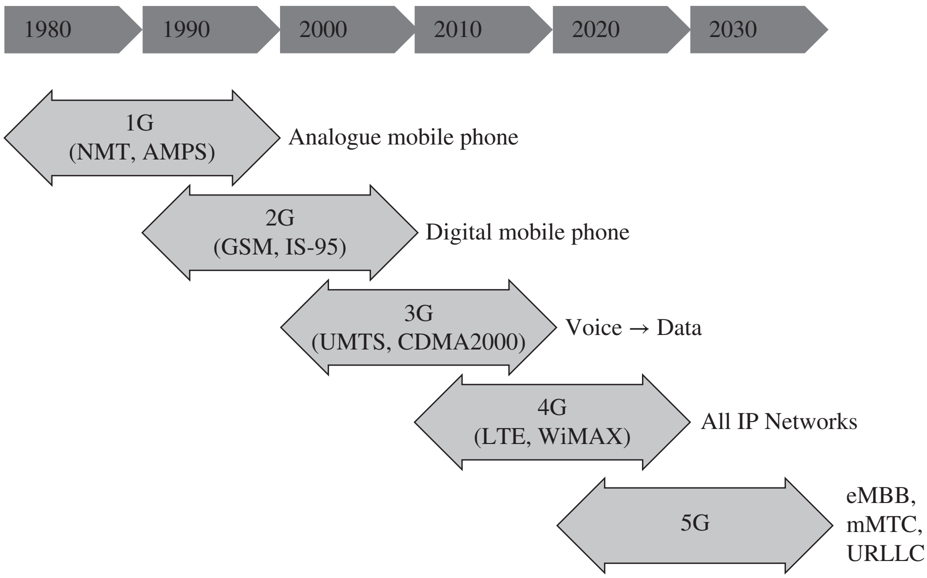

Figure 1.2 Evolution of cellular systems.

public safety, utilities, remote control, healthcare, education, Smart cities, wearables, Smart homes, agriculture, and enhanced multimedia. Among them, people pay attention to five key vertical sectors: automated driving, factory automation, smartgrids, eHealth, and augmented reality. In the next chapter, we look into their applications, system parameters and requirements. To sum up, 1G laid the foundation for mobile telephony, 2G popularized mobile telephony, 3G expanded mobile services from voice to data, 4G builds all IP core networks and achieves mobile broadband, and 5G includes new wireless features such as eMBB, URLL, and mMTC.

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