Wireless Networks

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5G System Design

An End to End Perspective

Second Edition

Springer

Wireless Networks

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To all the global health-care and other front-line workers who worked so tirelessly to take care of us during the Covid-19 pandemic.

Preface to the First Edition

It is hard to overstate the impact that HSPA and LTE technology have had on our global society. Mobile subscriptions for these technologies are now counted in the billions, touching lives and changing business everywhere on the planet. How did this come to pass? The dominance of these 3rd Generation Partnership (3GPP) technologies was not known a priori when their studies were first approved. There are many factors to explain the success, but surely these factors include the quality of the standards and technology as well as economies of scale from global deployment. For 5G, the fifth generation of telecommunication systems, the situation is different in that it is expected, even before the first equipment delivery, that 3GPP technology will dominate future global deployments. The vision for 5G also goes beyond traditional mobile broadband services. In 2015, ITU-R (International Telecommunication Union-Radio communications sector) established the 5G requirements for IMT-2020 (International Mobile Telecommunication system-2020), targeting diverse requirements from three key usage scenarios: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultrareliable and low-latency communication (URLLC).

Mobile broadband services like web browsing, social apps with text messaging, file sharing, music downloading, and video streaming are already very popular and supported by 4G communication systems. In the 5G era, these and other applications such as ultrahigh-definition (UHD) video, 3D video, and augmented reality (AR) and virtual reality (VR) will be better served with data rates up to hundreds of megabits per second or even gigabits per second. In addition, the demand of uplink high data rate service is also emerging, for example with HD video sharing. These service requirements, together with the anywhere anytime experience requirements with high user density and user mobility, define new limits for the eMBB scenario.

In the future, any object that can benefit from being connected will be connected, either partially or dominantly, through wireless technologies. This trend poses a huge demand for connecting objects/machines/things in a wide range of applications. Driverless cars, enhanced mobile cloud services, real-time traffic control optimization, emergency and disaster response, smart grid, e-health, and industrial communications, to name just a few, are all expected to be enabled or improved by wireless connectivity. By a closer observation of these applications, there are two major characteristics of these services: one is the number of desired connections; the other is the requested reliability within a given latency budget. These two significant characteristics drive the definitions of the mMTC and URLLC scenarios.

Accordingly, ITU-R defines the IMT-2020 requirements for all the above potential use cases, including eight key capabilities: 20 Gbps peak rate, 100 Mbps user perceived data rate at cell edge, 3 times spectrum efficiency of IMT-Advanced, mobility up to 500 km/h, low latency with less than 1 ms air interface round-trip time (RTT), connectivity density of 10 M connections per square kilometer, 100 times energy efficiency of IMT-Advanced, and traffic density with 10 Mbps per square meter. It is anticipated that the area traffic capacity is predicted to be increased by at least 100 times in 5G, with available bandwidth increased by 10 times. Altogether, the 5G system can provide a basic information infrastructure to be used by both people and machines for all of these applications, similar to the transportation system and electric power system infrastructure that we use now.

Each region in the world is planning their 5G spectrum. In Europe, multiple countries have allocated 5G spectrum mainly in C-band and released 5G operational licenses among mobile network operators. The UK has already auctioned 190 MHz sub-6 GHz spectrum for 5G deployment, with another 340 MHz low-frequency spectrum auction ongoing. In Asia, China has newly allocated 390 MHz bandwidth in 2.6 GHz, 3.5 GHz, and 4.9 GHz frequency bands among the three major operators for 5G deployment by 2020; Japan has allocated totally 2.2 GHz 5G spectrum including 600 MHz in C-band and 1.6 GHz in 28 GHz mm-wave spectrum among four mobile carriers, with 5G investment around JPY 1.6 trillion ($14.4 billion) over the next 5 years; South Korea has auctioned 280 MHz bandwidth in 3.5 GHz and 2.4 GHz bandwidth in 28 GHz spectrum for 5G network among the three telco carriers, with SKT having already released the first 5G commercial services since April 3rd, 2019. In the USA, 5G licenses are permitted in the existing 600 MHz, 2.6 GHz, and mm-wave frequency bands of 28 GHz and 38 GHz, with additional 3 millimeter-wave spectrum auctions in 2019 on 28 GHz, 24 GHz, as well as higher mm-wave spectrum at 37 GHz, 39 GHz, and 47 GHz. Europe, Asia, and North America have all announced early 5G network deployment by 2020.

This treatise elaborates on the 5G specifications of both the 5G new radio (5G-NR) and 5G new core (5G-NC) and provides a whole picture on 5G end-to-end system and key features. Additionally, this book provides the side-by-side comparison between 5G-NR and long-term evolution (LTE, also called as 4G) to address the similarities and the differences, which benefits those readers who are familiar with LTE system. 3GPP Release-15, i.e., the first release of 5G standard, has completed the standardization of both 5G non-stand-alone (NSA) and stand-alone (SA) architecture. 5G deployment will eventually go to SA deployment based on 5G new carrier (NC) with advanced core network features as slicing, MEC, and so on. Some operators, however, due to their business case balance between the significant investments and quick deployment, may consider NSA deployment from the beginning, i.e., with a primary connection to LTE and a secondary connection to NR. In addition to the network architecture, NR has built-in provisions in configuration and operation for coexistence with LTE. These include same-band (and even same channel) deployment of NR and LTE in low-band spectrum. An especially important use case is a higher frequency NR TDD deployment that, for coverage reasons, includes a supplemental uplink (SUL) carrier placed in an existing LTE band.

The book is structured into six main chapters. The first chapter looks at the use cases, requirements, and standardization organization and activities for 5G. These are 5G requirements and not NR requirements, as any technology that meets the requirements may be submitted to the ITU as 5G technology including a set of radio access technologies (RATs) consisting of NR and LTE, with each RAT meeting different aspects of the requirements. A second chapter describes, in detail, the air interface of NR and LTE side by side. The basic aspects of LTE that NR builds upon are first described, followed by sections on the NR-specific technologies such as carrier/channel, spectrum/duplexing (including SUL), LTE/NR coexistence, and new physical layer technologies (including waveform, polar/LDPC channel coding, MIMO, and URLLC/mMTC). In all cases, the enhancements made relative to LTE are made apparent. The third chapter contains description of NR procedures (IAM/beam management/power control/HARQ), protocols (CP/UP/mobility, including grant-free), and RAN architecture. The fourth chapter has a detailed discussion related to end-to-end system architecture, and the 5G Core (5GC), network slicing, service continuity, relation to EPC, network virtualization, and edge computing. The fifth chapter describes the ITU submission and how NR and LTE meet the 5G requirements in significant detail, from the rapporteur responsible for leading the preparation and evaluation. Finally, the book concludes with a look at the 5G market and the future.

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Preface to the Second Edition

In the 15 months since the publication of the first edition and the writing of this treatise, 3GPP has completed Release-16 of 5G. It has enhanced 5G with many features that were requested by the vertical industries. Loosely speaking, 5G Release-15 can be characterized as being optimized for the cellular eMBB service while 5G Release-16 is the beginning of the optimization of 5G for the vertical industries. It mainly focused on the support of the vehicular vertical and industrial Internet of Things. As such, we have significantly altered the first edition to cover the key features standardized in Release-16.

In particular, since the key focus of 5G Release-15 was on eMBB, it made sense to describe the key physical layer of NR in one chapter. That now no longer makes sense, and we have broken the chapter up into five chapters. The first two, Chaps. 2 and 3, describe the fundamental aspects of the LTE and NR air interface, respectively. By fundamental, we mainly mean the features that were needed to support eMBB services. The NR discussion in Chap. 3 has been enhanced with new discussions on MIMO enhancements, unlicensed access, positioning, and power savings. The other three chapters are new to the 2nd edition; Chaps. 7, 8, and 9 discuss the beginning of our journey on 5G support for the verticals (URLLC, V2X, industrial/manufacturing) after a complete end-to-end discussion of the fundamental aspects of 5G. The chapters are organized by verticals with descriptions of both Release-15 and -16 features that were developed in 3GPP mainly for that vertical contained in one place.

Chapter 4 contains the 5G RAN procedures, protocols, and architecture. It has been updated with the newly standardized beam management techniques and the IAB features. Other aspects standardized in Release-15 and -16 for the vertical industry have now been moved to their respective vertical chapters.

The end-to-end architecture is described in Chap. 5. This chapter has been enhanced with the newly standardized feature that accounts for the fact that there will exist a number of wireless technologies, some non-3GPP, for the user to access the Internet. As such, access traffic steering, switching, and splitting features were standardized in Release-16. These features enable a multi-access PDU connectivity service that allows one PDU session to be established with two simultaneous access connections, where one uses 3GPP access network and the other uses non-3GPP access network. The mechanisms for supporting non-3GPP access technology in 5G via untrusted non-3GPP access networks, trusted non-3GPP access networks, and wireline access networks are given. The chapter also discusses 5GC support for data analytics, cellular IoT, location services, and IMS.

Chapter 6 is a totally new chapter on 5G security. To ensure the entirety of 5G is secure, each architectural deployment model sports its own security architecture, features, and capabilities. The 5G security features, considerations, services, and capabilities are first described. Security enhancements that mainly targeted at the support of URLLC, CIoT, service-base architecture, network slicing, 5WWC, radio voice call continuity, vertical industries, and IAB are then each described. Not only does 5G need to be secure, but it has to also give assurance to other entity of its security in order to function as the wireless access part of a larger global network. Consequently, the last part of the chapter investigates 5G security assurance.

The 5G features that support URLLC are elucidated in Chap. 7. Physical layer changes to the PDCCH, UCI, and PUSCH that allow for transmissions with short latency and enhance reliability are introduced. Since URLLC services are likely to coexist with other services, mechanisms exist in the standards to allow for an efficient support of services with different requirements in the same band. DL preemption indication and CBG-based retransmissions to facilitate DL inter-UE multiplexing of UEs with different services have been specified in Release-15 while UL intra-UE prioritization and inter-UE multiplexing were specified in Release-16. From an end-to-end system perspective, Release-16 added redundant transmission and QoS monitoring for the URLLC service.

Chapter 8 focuses on the features for V2X service. It first gives a detailed description of the LTE V2X feature and then introduces the NR V2X sidelink feature by comparing and contrasting it to the V2X feature in LTE. The discussion will give an in-depth understanding of the physical structure, synchronization, physical layer and power control procedures, resource allocation and QoS and congestion control mechanism, layer 2/3 enhancements, as well as the architecture of the V2X feature. The operation was designed to work in both FR1 and FR2, but no effort was spent in Release-16 to optimize the FR2 operation. This optimization is widely expected to be the topic of future Releases of 5G.

Chapter 9 focuses on the features for the support of the OT (operational technology) industry. It starts with a discussion on how 5G enables the promise of *Industrie 4.0* and the ecosystem that is forming to facilitate 3GPP to support the OT industry. As countries recognize the importance of OT for their economy, spectrum bands are being allocated by the respective regulatory bodies for nonpublic networks to support the smart factories of the future. The bulk of the chapter will detail the enhancement in Release-16 for IIoT including the support of TSN by the 5GC.

Chapter 10 is now the chapter that describes the ITU submission and how NR and LTE meet the 5G requirements in significant detail, from the rapporteur responsible for leading the preparation and evaluation. A new section has been added to the chapter on the ITU evaluations since the last edition.

The last chapter was highly reworked. It starts, as in the last edition, with a discussion on the 5G market and argues that vertical industries are critical to the robust growth of the wireless industry. Instead of detailing the 5G trials next, it now contains a detailed discussion on global 5G deployments. It next discusses the trials for different verticals that are ongoing at different parts of the world. The chapter then ends with a look into the future and gives a description of what is anticipated to be in 5G Release-17 that is expected to be finalized in June of 2022.

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The authors would like to thank our colleagues from all over the world that participated in the different standardization and industrial fora for 5G development. It is through our collective hard labor in harmonization from which 5G was born. In addition, the efforts made by operators from all the three regions are appreciated very much, by identifying focused use cases, key features, and solutions, as well as prioritizing architecture option, spectrum bands, and terminal configurations, especially for the early deployment. Without this support, 3GPP can hardly complete the 5G standardization within such a short time. The first release of 5G standardization was done within 3 years, including study item and work item, which breaks the record in the history of 3GPP. Such an astonishing speed is a testimony to the joint cooperation and collaboration from all the members in the ecosystem, including operators, network vendors, devices, and chipset vendors. All from the industry are expecting 5G, and all have contributed to 5G standardization.

We also thank the editorial and publication staff at Springer Nature for their support of this manuscript; chief among them are Susan Lagerstrom-Fife, our editor for the first edition, as well as Mary James, our editor, and Shabib Shaikh, our project coordinator for the second edition.

Most importantly, we thank the support of our spouse/significant others and family members for putting up with the many days that we were away from home at the various meetings of the standard bodies and industry fora. But for 2020, we thank them for taking care of us while we were at home for almost the entire year with our virtual standards meeting that runs at all hours of the day and night.

Contents

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Abbreviations

3GPP	3rd Generation Partnership Project
5GAA	5G Automotive Association
5GACIA	5G Alliance for Connected Industries and Automation
5GC	5G core network
5G-RG	5G Residential Gateway
5GS	5G system
5GWWC	5G Wireless and Wireline Convergence
AAnF	AKMA Anchor Function
AES	Advanced Encryption Standard
AF	Application function
AKA	Authentication and key agreement
AKMA	Authentication and key management for applications
AM	Acknowledged mode
AMBR	Aggregate maximum bit rate
AMC	Adaptive modulation and coding
AMF	Access and mobility management function
AoA	Angle of arrival
AoD	Angle of departure
APRF	Authentication credential Repository and Processing Function
ARP	Allocation and retention priority
A-S	Access-Stratum (Note that this abbreviation is AS in 3GPP, which overloaded the abbreviation with application server. A different abbreviation from 3GPP is used in this treatese for clarity)
AS	Application server
AUSF	Authentication server function
AV	Authentication vectors
BFR	Beam failure recovery
BLER	Block error rate
BM-SC	Broadcast multicast service center
BSSID	Basic service set identifier
BWP	Bandwidth part

CA	Carrier aggregation
CAG ID	Closed access group identifier
CAG	Closed access group
CBG	Code block group
CBGTI	CBG transmission information
CC	Component carrier or in security assurance context common criteria
CCE	Control channel element
CCRA	Common Criteria Recognition Arrangement
CDF	Cumulative distribution function
CDM	Code division multiplexing
C-DRX	Connected-mode discontinuous reception
CE	Controlled element
CF	Correction field
CG	Configured grant
CH	Compressed header
CM	Cubic metric
CMP	Cubic metric preserving
CNC	Centralized network configuration
CORESET	Control resource set
COT	Channel occupancy time
CP	Cyclic prefix
CP-OFDM	Cyclic Prefix-Orthogonal Frequency-Division Multiplexing
CQI	Channel quality indication
CRB	Common resource block
CRI	CSI-RS resource indicator
CRS	Cell-specific reference signal
CSG	Closed subscriber group
CSI	Channel state information
CSI-IM	Channel state information-interference measurement
CSI-RS	CSI reference signal
CTCPEC	Canadian Trusted Computer Product Evaluation Criteria
CU	Centralized unit
D2D	Device to device
DC	Dual connectivity
DCI	Downlink control information
DCN	Dedicated core network
DFT	Digital Fourier transform
DM-RS	UE-specific reference signal (also known as “demodulation reference signal”)
DN	Data network
DNAI	Data network access identifier
DNS	Domain name system
DRB	Dedicated radio bearer
DRS	Discovery reference signal
DRX	Discontinuous reception

DS-TT	Device-side TSN translator
DTLS	Datagram Transport Layer Security
DU	Distributed unit
EAP	Extensible Authentication Protocol
EC-GSM	Extended coverage for GSM
E-CID	Enhanced-Cell ID
ECIES	Elliptic Curve Integrated Encryption Scheme
EDT	Early data transmission
EHC	Ethernet header compression
eIMTA	Enhanced interference management traffic adaption
eLCS	Enhanced location services
eMBB	Enhanced mobile broadband
eMTC	Enhanced machine-type communication
eNB	Enhanced Node B
EN-DC	E-UTRA-NR dual connectivity
eNodeB	Evolved NodeB (the base station for LTE radio)
EPDCCH	Enhanced physical downlink control channel
EPS	Enhanced packet core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network (LTE access network)
FD	Full duplex
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FeMIMO	Further enhanced MIMO
FH	Full header
FN-RG	Fixed Network Residential Gateway
FR	Frequency range
FR1	Frequency range 1 (below 6 GHz)
FR2	Frequency range 2 (above 6 GHz)
FSTD	Frequency switched transmit diversity
GAA	Generic Authentication Architecture
GBA	Generic Bootstrap Architecture
GBR	Guaranteed bit rate
GM	Grand master
gNB	g-node B (NR node B)
GoS	Grade of service
gPTP	Generalized Precision Time Protocol
GSCN	Global synchronization channel number
GTP-U	General Packet Radio System (GPRS) Tunnelling Protocol User Plane
GUTI	Globally unique temporary identifier
HeNB	Home enhanced node B
HPLMN	Home PLMN
hSEPP	Home Security Edge Protection Proxy
HSS	Home subscriber server
HST	High-speed train

IAB	Integrated access and backhaul
IAM	Initial access and mobility
IIoT	Industrial Internet of Things
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IMT	International mobile technology
IoT	Internet of Things
IPX	IP Packet Exchange
ITSEC	Information Technology Security Evaluation Criteria
ITU	International Telecommunication Union
ITU-R	ITU-Radiocommunication sector
L.MBMS	Local MBMS
L1-SNR	Layer 1 (physical layer) SNR
LAA	License-assisted access
LBRM	Limited buffer rate matching
LBT	Listen before talk
LI	Layer indicator
LOS	Line-of-sight
LPWA	Low-power wide area
LTE	Long-term evolution
LTE-U_U	The reference point between the E-UTRAN and the UE
LTE-V	Long-term evolution-vehicle
MAPSEC	Mobile application part security
MBMS	Multimedia broadcast and multicast services
MBS	Multicast and broadcast services
MBSFN	MBMS Single-Frequency Network
MCC	Mobile country code
MCE	Multi-cell/multicast coordination entity
MCL	Maximum coupling loss
MCOT	Maximum channel occupancy time
MCS	Modulation coding scheme
MIB	Master information block
MIMO	Multiple input multiple output
MME	Mobility management entity
mMTC	Massive machine-type communication
MO	Mobile Originated
MSD	Maximum sensitivity deduction
MTC	Machine-type communication
N3IWF	Non-3GPP Interworking Function
NAI	Network access identifier
NAS	Non-access stratum
NB-CIoT	NarrowBand cellular IoT
NB-IoT	Narrow Band-Internet of Things
NB-M2M	Narrow Band M2M
NC-JT	Non-coherent joint transmission

NDS	Network domain security
NE-DC	NR-E-UTRA dual connectivity
NEF	Network exposure function
NESAS	Network Equipment Security Assurance Scheme
NGEN-DC	NG-RAN E-UTRA-NR dual connectivity
NGMN	Next-generation mobile networks
NID	Network identifier
NIDD	Non-IP data delivery
NLOS	Non-line-of-sight
NR	New radio
NRF	Network repository function
NSA	Non-stand-alone
NSaaS	Network slice as a service
NSSAFF	Network Slice Specific Authentication and Authorization Function
NSSAI	Network slice selection assistance information
NSSF	Network slice selection function
NW-TT	Network-side TSN translator
NZP	Nonzero power
OCC	Orthogonal cover code
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal frequency division multiple access
OS	OFDM symbol
PAPR	Peak-to-average power ratio
PBCH	Physical broadcast channel
PC5	The sidelink interface for V2X communications
PCC	Primary component carrier
PCF	Policy control function
PCFICH	Physical control format indicator channel
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channel
PDU	Protocol Data Unit
PF	Paging frame
PGW	Packet gateway
PHICH	Physical hybrid ARQ indicator channel
PKI	Public Key Infrastructure
PLMN	Public land mobile network
PMCH	Physical multicast channel
PMI	Precoding matrix indicator
PMI	Precoding matrix indicator
PNiNPN	Public network integrated nonpublic network
PO	Paging occasion
PRACH	Physical random access channel
PRB	Physical resource block
PRG	Precoding resource block groups

PSA	PDU session anchor
PSM	Power saving mode
PSS	Primary synchronization signal
PTM	Point to multipoint
PTP	Point to point
PT-RS	Phase tracking reference signal
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QCL	Quasi-co-location
QoS	Quality of service
QRO	Quasi-row orthogonal
RAN	Radio access network
RAR	Random access response
RB	Resource block
RedCap	Reduced capacity
REG	Resource element group
RI	Rank indication
RIT	Radio Interface Technology
RLC	Radio link control
RMSI	Remaining master system information
RN	Relay node
RRC	Radio resource control
RRM	Radio resource management
RS	Reference signal
RSFP	RAT frequency selection priority
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RSU	Roadside unit
RTT	Round-trip time
S1 AP	S1 application protocol
SAS	Security accreditation scheme
SBA	Service-based architecture
SBI	Service-based interfaces
SCAS	Security Assurance Specification
SCC	Secondary component carrier
SCell	Secondary cell
SC-FDMA	Single-carrier-frequency division multiple access
SC-PTM	Single-cell point-to-multipoint transmission
SCS	Subcarrier spacing
SD	Slice differentiator
SDAP	Service data adaptation protocol
SDL	Supplementary downlink
SEAF	Security Anchor Function
SECAM	Security Assurance Methodology
SECOP	Service Communication Proxy

SEPP	Security edge protection proxies
SFBC	Space frequency block coding
SFN	System Frame Number
SGW	Serving Gateway
SI	Study item
SIB	System information block
SIDF	Subscription Identifier De-concealing Function
SIM	Subscriber Identity Module
SINR	Signal-to-interference plus noise ratio
SLA	Service-level agreement
SMF	Session management function
SMS	Short message service
SNPN	Stand-alone nonpublic network
SPS	Semi-persistent scheduling
SR	Scheduling request
SRI	SRS resource indicator
SRIT	Set of Radio Interface Technologies
SRS	Sounding reference signal
S-RSRP	Sidelink reference signal received power
SRVC	Single radio voice call continuity
SS	Search space
SS7	Common Channel Signaling System 7
SSB	Synchronization signal/PBCH block
SSBRI	SSB resource indicator
SSID	Service Set Identifier
SSS	Secondary synchronization signal
SST	Slice/service type
SUL	Supplementary uplink
SUPI	Subscription permanent identifier
TBCC	Tail-biting convolutional code
TBS	Transport block size
TCI	Transmission configuration indicator
TCSEC	Trusted Computer Security Evaluation Criteria
TDD	Time division duplex
TDMA	Time division multiple access
TDoA	Time difference of arrival
TDRA	Time domain resource allocation
telco	Telephone company
TLS	Transport Layer Security
TM	Transmission mode
TMSI	Temporary Mobile Subscriber Identity
TPMI	Transmit precoding matrix indicator
TRI	Transmit rank indicator
TRP	Transmit/receive point
TRS	Tracking reference signal

TS	Time slot
TSC	Time-sensitive information
TSe	Egress timestamp
TSi	Ingress timestamp
TSN AF	TSN adaption function
TSN	Time-sensitive network
TTI	Transmission time interval
UCI	Uplink control information
UDM	Unified data management
UDR	Unified data repository
UICC	Universal integrated circuit card
UL CI	Uplink cancellation indication
UM	Unacknowledged mode
UMa	Urban macro cell
UMi	Urban micro cell
UPF	User plane function
UPGF	User Plane Gateway Function
URLLC	Ultrareliable and low-latency communication
URSP	UE route selection policy
USD	User service descriptions
USIM	User Subscriber Identity Module
V2X	Vehicle to Everything
VPLMN	Visited Public Land Mobile Network
vSEPP	Visited Security Edge Protection Proxy
W-5GAN	Wireline 5G Access Network
WRC	World Radiocommunication Conference
WUS	Wake-up signal
XR	Extended reality
ZP	Zero power

Chapter 1
From 4G to 5G: Use Cases and Requirements

This chapter investigates the motivations and driving forces of 5G development as well as introduces the 5G use cases and technical requirements. 5G is the first generation that devotes itself to connecting both humans and machines. Accordingly, the service requirements and the technical performance requirements are extended from mobile broadband (MBB) to the new use cases. The diverse requirements pose significant challenges to system design.

This chapter also presents how 5G development is made based on industry collaboration, where ITU-R and 3GPP play the central role in this process. It introduces and reviews the ITU-R procedure on IMT-2020 development and 3GPP 5G standardization process. With the guidance of ITU-R and the well-harmonized technical development in 3GPP, 5G technology is well developed; which is one of the major keys for 5G success.

1.1 Introduction

Mobile cellular network has been developing since the 1970s.[1] The first-generation (1G) mobile network was based on frequency division multiple access (FDMA) (Fig. 1.1). It provided analog voice service to mobile users. After approximately 10 years, time division multiple access (TDMA) was developed in the second-generation (2G) network which enabled the digital voice service and low data rate service. In mid-1990 to 2000s, coding division multiple access (CDMA) was employed to develop the third-generation (3G) mobile network. The CDMA access enabled more efficient multiple user access through the specified bandwidth. By this means,

[1] Illinois Bell Telephone Co. conducted a trial development cellular system in the Chicago area in 1979. Full commercial service began in Chicago in October of 1983.

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