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An End to End Perspective

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In memory of Kim Chang, our colleague who passed away at a standards meeting in Japan.

Preface

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 Third 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 ultra-reliable and low latency communication (URLLC).

Mobile broadband services like web browsing, social apps with text messaging, file sharing, music downloading, video streaming, and so on are already very popular and supported by 4G communication systems. In the 5G era, these and other applications such as ultra-high 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 any-time 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 10M 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 infrastructures 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 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 mm-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-standalone (NSA) and standalone (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. For 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 co-existence, 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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We also thank the editorial and publication staff at Springer Natural for their support of this manuscript; chief among them our editor Susan Lagerstrom-Fife, editorial assistance Karin Pugliese and production project manager Mohanarangan Gomathi.

Most importantly, we thank the support of our 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.

Acronyms

3GPP	3rd Generation Partnership Project
5GAA	5G automotive association
5GACIA	5G alliance for connected industries and automation
5GC	5G core network
AMBR	Aggregate maximum bit rate
AMC	Adaptive modulation and coding
AMF	Access and mobility management function
ARP	Allocation and retention priority
AS	Application server
AUSF	Authentication server function
BLER	Block error rate
BWP	Bandwidth part
CA	Carrier aggregation
CBG	Code block group
CBGTI	CBG transmission information
CC	Component carrier
CCE	Control channel element
CDF	Cumulative distribution function
CM	Cubic metric
CMP	Cubic metric preserving
CORESET	Control resource set
CP	Cyclic prefix
CQI	Channel quality indication
CRB	Common resource block
CRI	CSI-RS resource indicator
CRS	Cell-specific reference signal
CSI	Channel State Information
CSI-IM	Channel state information-interference measurement
CSI-RS	CSI reference signal
D2D	Device to device
DC	Dual connectivity

DCI	Downlink control information
DCN	Dedicated core network
DM-RS	UE-specific reference signal (also known as "demodulation reference signal")
DN	Data network
DRS	Discovery reference signal
EC-GSM	Extended coverage for GSM
EDT	Early data transmission
eIMTA	Enhanced interference management traffic adaption
eMBB	Enhanced mobile broadband
eMTC	Enhanced machine type communication
EN-DC	E-UTRA-NR dual connectivity
EPDCCH	Enhanced physical downlink control channel
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FR	Frequency range
FSTD	Frequency switching transmit diversity
GBR	Guaranteed bit rate
GoS	Grade of service
GSCN	Global synchronization channel number
GUTI	Globally unique temporary identifier
IAM	Initial access and mobility
IMT	International mobile technology
IoT	Internet of things
ITU	International telecommunication union
ITU-R	ITU-Radiocommunication sector
LAA	License assisted access
LBRM	Limited buffer rate-matching
LI	Layer indicator
LPWA	Low power wide area
LTE	Long-term evolution
MBMS	Multimedia broadcast multicast services
MBSFN	MBMS Single-Frequency Network
MCL	Maximum coupling loss
MCS	Modulation coding scheme
MIB	Master information block
MIMO	Multiple input multiple output
MME	Mobility management entity
mMTC	Massive machine type communication
MSD	Maximum sensitivity deduction
MTC	Machine type communication
NAS	Non-Access Stratum
NB-CIoT	NarrowBand cellular IoT
NB-IoT	Narrow Band-Internet of Things
NB-M2M	Narrow Band M2M

NE-DC	NR-E-UTRA dual Connectivity
NGEN-DC	NG-RAN E-UTRA-NR dual Connectivity
NGMN	Next generation mobile networks
NR	New radio
NSA	Non-standalone
NSSAI	Network slice selection assistance information
NZP	Non-zero power
OCC	Orthogonal cover code
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal frequency division multiple access
PAPR	Peak to average power ratio
PBCH	Physical broadcast channel
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
PF	Paging frame
PGW	Packet gateway
PHICH	Physical hybrid ARQ indicator channel
PLMN	Public land mobile network
PMCH	Physical multicast channel
PMI	Precoding matrix indicator
PO	Paging occasion
PRACH	Physical random access channel
PRB	Physical resource block
PRG	Precoding resource block groups
PSM	Power saving mode
PSS	Primary synchronization signal
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
REG	Resource element group
RI	Rank indication
RMSI	Remaining master system information
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
RTT	Round trip time
SBA	Service-based architecture
SCC	Secondary component carrier
SC-FDMA	Single carrier-frequency division multiplexing access
SC-PTM	Single-cell point to multipoint transmission
SCS	Sub-carrier spacing
SD	Slice differentiator
SDAP	Service data adaptation protocol
SDL	Supplementary downlink
SEPP	Edge protection proxies
SFBC	Space frequency block coding
SFN	System Frame Number
SGW	Serving Gateway
SI	Study item
SIB	System information block
SINR	Signal to interference plus noise ratio
SLA	Service level agreement
SMF	Session management function
SMS	Short message service
SR	Scheduling request
SRI	SRS resource indicator
SRS	Sounding reference signal
SSB	Synchronization signal/PBCH block
SSBRI	SSB resource indicator
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
TDD	Time division duplex
TDMA	Time division multiple access
telco	Telephone company
TM	Transmission mode
TPMI	Transmit precoding matrix indicator
TRI	Transmit rank indicator
TRS	Tracking reference signal
TS	Time slot
TTI	Transmission time interval
UCI	Uplink control information
UDM	Unified data management

UPF	User plane function
URLLC	Ultra-reliable and low latency communication
URSP	UE route selection policy
V2X	Vehicle to Everything
WRC	World radiocommunication conference
WUS	Wake up signal
ZP	Zero power

Contents

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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. ITU-R procedure on IMT-2020 development is introduced, and 3GPP 5G standardization process is reviewed. 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, the data rate can reach several kilo bits per second to several mega bits per second, which enables fast data transmission for multimedia.

[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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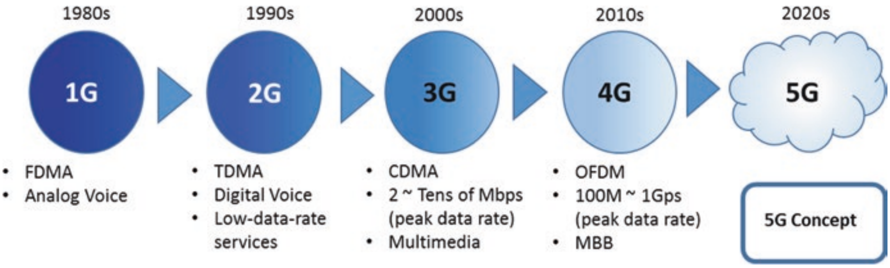

Fig. 1.1 A schematic view of the history of cellular communications

By the mid-2000s, ubiquitous data began to transform the meaning of mobile telephony service. The ever-increasing demand on data service stressed the capability of the 3G mobile network. Users are expecting to connect to the network anywhere, on the go or at home. More frequent data transmission happens, and faster data rates are becoming essential. Users start demanding broadband experience from their wireless mobile network service.

In 2005, the industry started the development of the fourth generation (4G) mobile network that aims to provide ubiquitous mobile broadband (MBB) service. 3GPP developed the Long Term Evolution (LTE) that employs Orthogonal Frequency Division Multiple Access (OFDMA) to offer a good compromise on multi-user data rates and complexity. LTE development received a wide range of industry support. The OFDMA concept is well incorporated with multiple-input multiple-output (MIMO) technology, and the complexity is significantly reduced.

International Telecommunication Union (ITU), especially its Radiocommunication Sector (ITU-R), has played an important role in mobile network development since 3G. Due to the great success of 1G and 2G mobile networks, the industry and research interests were increased exponentially for 3G development. Therefore, many stakeholders were involved in 3G development with respect to previous generation mobile networks. A global standardization was becoming necessary due to the involvement of a variety of network vendors, user terminal manufacturers, and chipset providers. Global spectrum harmonization also becomes a critical issue for the successful development and deployment of the mobile network. In order to harmonize the spectrum use in different regions for appropriate technologies for 3G mobile network, ITU-R established procedures to address the allocation of spectrum for 3G mobile network, and to identify the appropriate radio interface technology that could be deployed on those spectrums globally. In this context, International Mobile Technology-2000 (IMT-2000) was specified by the ITU, where a family of technologies were identified as radio interface technologies for 3G mobile network (IMT-2000 system). Such procedures provide fair opportunity for the proponents that are interested in mobile network development, as well as set the necessary performance requirements to guarantee that candidate technology can effectively meet the requirements. The procedure is further developed and applied to 4G and 5G development in ITU-R. This resulted in the IMT family specification: IMT-2000 for "3G," IMT-Advanced for "4G," and IMT-2020 for "5G."

While ITU-R plays the central role for defining appropriate technology for each generation of mobile network, the technology development is conducted in standard development organizations (SDOs). In 1998, the third generation partnership project (3GPP) was initiated by the key players of the mobile network development, and gains the support from six regional SDOs from Europe, China, Japan, Korea, and America. It lays the foundation of global development for mobile technologies, and attracts the participation of a variety of industry and academy players. 3GPP has grown to be the essential standard organization for technology development for mobile networks since 3G.

1.2 Global 5G Development

In July 2012, ITU-R started the development of the vision for IMT for 2020 and beyond, which is later known as "IMT-2020." Following the ITU-R activity, in 2013 to 2015, several regional promotion groups and research forums were established in China, Europe, Korea, Japan, and America for 5G development. The regional studies provided extensive investigations of 5G use cases and capability requirement, which formed a global foundation for 5G vision developments in ITU-R. In 2015, the 5G vision was set up in ITU-R based on the regional convergence.

Along with the gradual maturity of the 5G vision, in late 2014, 5G technology studies received increasing attention from industry and academy: with many new technologies and concepts proposed. In 2015, when ITU-R created the 5G vision, 3GPP as one of the most widely supported global standardization organizations started the technical requirement study and deployment scenarios investigation, targeting to fulfilling the 5G vision. In 2016, 3GPP initiated the 5G new radio (NR) technology study. Industry members, institutions, and universities are actively engaged in 3GPP study, which form the solid foundation for 5G radio interface technology that encompasses a wide range of usage scenarios and features.

In December 2017, 3GPP accomplished the first milestone of 5G specification. An initial characteristics description was submitted to ITU-R in February 2018. The ongoing global 5G development opens the gate to the fully connected world. The global harmonization and coordination are the essential keys throughout the 5G development.

1.2.1 ITU-R Development on 5G/IMT-2020

For different radio services to coexist, it must rely on the allocated spectrum resources to deliver their capability. ITU-R is responsible for coordinating the spectrum allocation and spectrum usage for many different radio services, including satellite, broadcast, scientific research, and mobile service. The radio spectrum resources are rather limited and, thus, efficient use of spectrum by each of the radio services should be guaranteed. This is also part of the responsibility of the ITU-R. It conducts technology studies to continuously improve the efficiency of spectrum usage, and compatibility studies are conducted among the radio services to make sure different radio services with appropriate spectrum allocation can coexist in an efficient manner. To this end, a range of study groups (SGs) and, under a specific SG, a number of working parties (WPs) are established in ITU-R. The technical and spectrum experts with rich expertise on related fields are gathered under WPs and SGs for the study of applying appropriate technologies for the specific radio services, and to investigate the spectrum allocation for specific radio service purposes.

WP 5D is the expert group under SG 5 for the study of International Mobile Technology (IMT) services in ITU-R. To guarantee that the IMT technologies can utilize the spectrum efficiently, and can well coexist with other radio services, the expert group devotes itself to develop a globally implemented radio interface standard that has high spectral efficiency and other key capabilities, which are widely supported by a variety of network vendors, user terminal manufacturers, and chipset providers.

The history of the development of IMT-2000 (3G), IMT-Advanced (4G), and IMT-2020 (5G) is depicted in Fig. 1.2 (see also [1]).

As seen from Fig. 1.2, ITU-R usually spent around 10 years for development of each generation of the mobile network (or IMT network under ITU-R context). From IMT-Advanced, a vision development was always made before the technical development. The vision study usually covers the investigation of high-level requirements, use cases, and key capabilities desired by the next generation mobile network. This is becoming an important step to converge the regional desires from different parts of the globe. It is observed that one ITU-R study period (3–4 years) is usually

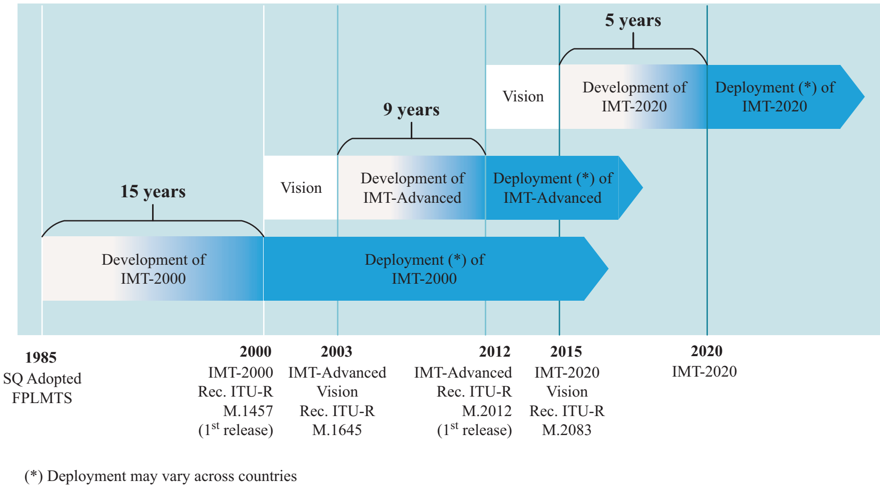

Fig. 1.2 Overview of timeline for IMT development and deployment

spent for this purpose. After that, another one to two (or even more) study periods are used to develop the technical aspects and to conduct the compatibility study if the new IMT spectrum that is requested are already used by other radio services. The time plan might be depending on the technical complexity of technology to achieve the vision, and the new spectrum it may utilize to reach the demanded capability.

For 5G development, the vision study was from 2012 to 2015. During this time period, regional 5G promotion groups and research forums were established to gather and converge the regional interest of 5G vision, and the regional views are contributed to ITU-R through the representative administration members and sector members.

From 2015, ITU-R started the technical development of 5G which aims to define an IMT-2020 (5G) global specification by October 2020. The technical development phase usually contains the definition of minimum technical requirements and evaluation guidelines, as well as an IMT-2020 submission and evaluation procedure. The minimum technical requirements guarantee that the candidate proposal can achieve the vision and can utilize the spectrum (including the potential new IMT spectrum) effectively. The submission and evaluation procedure defines the criteria of acceptance for IMT-2020 proposal, the procedure of inviting external organizations to submit IMT-2020 proposal, inviting the independent evaluation groups to evaluate the proposal, as well as ITU-R's procedure of approving the proposal. Following the ITU-R procedure, external organizations like 3GPP initiated their technical development of 5G from 2015 which will be reviewed in Sect. 1.2.3. More detailed discussion on the 5G timeline and the submission and evaluation procedure can be found in Sect. 1.4.

Concurrently ITU-R also started the compatibility study of potential new spectrum for 5G deployment. Such studies consist of two parts. One part is for the new IMT spectrums that were allocated in world radio communication conference (WRC) 2015. For example, the frequency range of 3.3–3.8 and 4.5–4.8 GHz (usually referred to as C-band) were identified as IMT spectrum globally or regionally. ITU-R continued to study the remaining issues on compatibility study on these bands in WP 5D. The other part is for potential new IMT spectrums that will be discussed at WRC-19. ITU-R has already begun its work on evaluating new spectrum by requesting technical development on feasible technologies to guarantee the efficient use of these potential new bands, and the compatibility studies to guarantee that they can efficiently coexist with other radio services.

The 5G spectrum will be discussed in more detail in Sect. 2.3.1.1.

1.2.2 Regional Development/Promotion on 5G

After ITU-R started 5G vision study in 2012, several regional promotion groups and research forums were founded in China, Europe, Korea, Japan, and America. These regional activities includes the study of 5G requirements, use cases, and deployment scenarios, as well as exploring the key technologies and the nature of 5G spectrum. These activities are briefly discussed in this section.

1.2.2.1 NGMN

Next Generation Mobile Networks (NGMN) is an alliance with worldwide leading operators and vendors that aims to expand the communications experience which will bring affordable mobile broadband services to the end user. It has a particular focus on 5G while accelerating the development of LTE-Advanced and its ecosystem.

NGMN published the "5G white paper" [2] in Feb 2015 which provided a list of requirements from the operator perspective to 5G networks. The requirements indicated a demand for capacity increase and the uniform user experience data rate across urban areas to rural areas. It also indicated that 5G networks should be capable of delivering diverse services including massive internet of things like sensor networks, extreme real-time communications like tactile internet, and ultra-reliable communications like e-Health services, to name a few. The services should be delivered in diverse scenarios, including high-speed trains, moving hotspots, and aircrafts. Such diversity fits in ITU's envisioned 5G use cases as described in Sect. 1.3.

1.2.2.2 IMT-2020 (5G) Promotion Group

In February 2013, the IMT-2020 (5G) promotion group was established in China by three ministries: the Ministry of Industry and Information Technology (MIIT), the National Development and Reform Commission, and the Ministry of Science and Technology. It is the major platform to promote the research and development of 5G in China. The promotion group consists of leading Chinese operators, network equipment vendors, research institutions, and universities.

The IMT-2020 (5G) promotion group published its 5G vision white paper [3] in May 2014. The white paper indicated two important 5G usage categories: mobile broadband and internet of things. The mobile broadband use cases will continue to be addressed by 5G network that provides 1 Gbps user experienced data rate in many deployment scenarios. The internet of things use cases on the other hand would be the other major driver to 5G network deployment, which requires a very capable 5G network to provide massive connections, very low latency, and high reliability. This forms a first overview of 5G use cases that were later developed into three 5G usage scenarios identified by ITU-R.

1.2.2.3 Europe: 5G PPP

The 5G Infrastructure Public Private Partnership (5G PPP) is a joint initiative between the European Commission and European ICT industry for 5G study in Europe. The first phase of 5G PPP started from July 2015, and continued to its second phase in 2017.

Before the first phase of 5G PPP initiative, an important 5G project was founded in Nov 2012, called Mobile and wireless communications Enablers for

Twenty-twenty (2020) Information Society (METIS). In April 2013, METIS published their study on 5G use cases, requirements, and scenarios (see [4]). In this study, METIS mentioned a number of new industrial and machine type communications for 5G besides mobile broadband applications. In April 2015, METIS summarized these use cases into three categories in [5], in accordance with ITU-R development on 5G use cases. The three use cases are extreme mobile broadband (xMBB), massive machine-type communications (mMTC), and ultra-reliable machine-type communications (uMTC), which is converged to ITU-R vision on 5G requirement and use cases as will be discussed in Sect. 1.3.1.

1.2.2.4 Korea: 5G Forum

The 5G Forum was founded by the Ministry of Science, ICT and Future Planning and mobile industries in Korea in May 2013. The members of 5G Forum consisted of mobile telecommunication operators, manufacturers, and academic professionals. The goal of the 5G Forum is to assist in the development of the standard and contribute to its globalization.

Five core 5G services were foreseen by the 5G forum, including social networking services; mobile 3D imaging; artificial intelligence; high-speed services; and ultra- and high-definition resolution capabilities; and holographic technologies. Such new services will be enabled by the 5G network with powerful capabilities that provide ultra-high capacity and data rates.

1.2.2.5 Japan: 5GMF

The Fifth Generation Mobile Communications Promotion Forum (5GMF) was founded in September 2014 in Japan. 5GMF conducts research and development related to 5G including the standardization, coordination with related organizations, and other promotion activities.

5GMF published the white paper "5G Mobile Communications Systems for 2020 and beyond" [6] in July 2016, which highlighted the 5G use cases of high data rate services, self-driving, location-based services, etc. It foresaw that 5G network needs to be extremely flexible to reach the requirements of these diverse requirements.

1.2.2.6 North and South America: 5G Americas

5G Americas is an industry trade organization composed of leading telecommunications service providers and manufacturers. It was continued in 2015 from the previously known entity: 4G Americas. The organization aims to advocate for and foster the advancement and full capabilities of LTE wireless technology and its evolution beyond to 5G, throughout the ecosystem's networks, services, applications, and wirelessly connected devices in the Americas. 5G Americas is invested in developing a connected wireless community while leading 5G development for the Americas.

5G Americas published its white paper on 5G Services and Use Cases [7] on November 2017. It provided an insightful report on 5G technology addressing new trends in a broad range of use cases and business models, with technical requirements and mappings to 5G capabilities. This is a continued study on 5G use cases for future uses.

1.2.2.7 Global 5G Event

The 5G regional developments call for a global coordination to form a unified 5G standard that is applicable worldwide. The regional 5G developers, including IMT-2020 (5G) PG, 5G PPP, 5G forum, 5GMF, 5G Americas, and 5G Brazil, have answered this call by setting up global 5G event to share the views and development status in each region. These events will be instrumental in building global consensus on 5G with the world's 5G promotion organizations. This series of events have been putting its efforts in promoting the usage of 5G for different vertical industries, 5G eco-systems and invite key industry players, administrations and regulators to participate in the discussion.

The first global 5G event was hosted by IMT-2020 PG in Beijing, May 2016, and the event is held twice a year in rotation. The next event will be at Valencia, Spain, in June 2019.

1.2.3 Standard Development

Along with ITU-R and regional activities towards 5G development, standardization organizations have also focused their attention on 5G since 2014. The global partnership project, 3GPP, has become the key standard organization of 5G development. It has become a global initiative for mobile cellular standard since the development of the 3G network. The current 4G, LTE mobile broadband standard is one of the most successful mobile standards and it is used worldwide.

3GPP is an organization that unites telecommunications standard development organizations (SDOs) all over the world. These SDOs are known as organization partners (OPs) in 3GPP, and currently there are seven OPs: ARIB and TTC from Japan, ATIS from America, CCSA from China, ETSI from Europe, TSDSI from India, and TTA from Korea. The seven OPs provide the members with stable environment to develop 3GPP technology. The OP members include key industry players, leading operators, vendors, user terminal manufacturers, and chipset developers. Research institutes with regional impacts, academic organizations and universities are also included. It covers almost all the key parties as far as a mobile cellular standard is concerned. The members of the OPs are heavily involved in the technical standard development, which ensure the 3GPP technology addresses the concerns and issues from different parties and different regions. Based on the consensus of the members from different OPs, the technical specifications defined by 3GPP are transposed by the OPs into their regional specifications. By this means, global mobile standards are developed. It can be argued that this is the essential key for the success of 3GPP standard development.

LTE is an early example under this consensus-based spirit of development. The global and wide range participation laid the foundation for the success of LTE development, standardization, and implementation. Due to the great success of LTE, 3GPP has become the essential standard development body for 5G. In late 2014, 3GPP initiated 5G studies and development along with the gradual maturing of the 5G vision.

During late 2015 to early 2017, when 3GPP was in its 14th release time frame (known as Release-14), 5G studies on technical requirements and deployment scenarios were conducted. These studies aimed to achieve the 5G vision as defined by ITU-R in June 2015. The study of a new radio (NR) interface was initiated following the requirement study. The key technical components were identified for the NR development, which form the basis of the specification work in the next release (i.e., Release-15) that last from early 2017 to June 2018. It is planned that a full capability 3GPP 5G technology, including NR and LTE, will be developed in Release-16 during the time frame of 2018 to the end of 2019. With this phased approach, 3GPP will bring its 5G solution to ITU-R as IMT-2020 in the year 2020.

1.3 Use Case Extensions and Requirements

Cellular communication system, from its first generation, is focused on connecting humans. The 1G and 2G communication system provided ubiquitous voice service between persons, which enables us to talk freely to our friends when we are at home, in office, or on the move. From 3G to 4G, multimedia and other mobile broadband applications are supported, and we are able to do much more, such as browsing the web, sharing nice pictures with our friends, and chatting on short videos, while on the move. For 5G, however, the study of the use cases reveals some new demands that are beyond the mobile broadband (MBB) which primarily aims to connect human beings and machines. This section provides a review of 5G use cases, requirements, and key capabilities.

1.3.1 5G Usage Cases and Service Requirement

5G communication is envisioned to enable a full connected world for 2020 and beyond. This full connectivity is targeted not only to communicating the people, but also enables the communication of machines and things that can bring added value to improving the operational efficiency of the society, and facilitate our everyday life. Under this vision, 5G use cases are extended from mobile broadband (MBB) to internet of things (IoT).

1.3.1.1 Extended Usage Scenarios: From eMBB to IoT (mMTC and URLLC)

ITU-R established the 5G vision in 2015 through its Recommendation ITU-R M.2083 [1], indicating that 5G will extend its usage scenario from enhanced mobile broadband (eMBB) to massive machine type communication (mMTC) and ultra-reliable and low latency communication (URLLC). The mMTC and URLLC services are a subset of internet of things (IoT) services. They are considered as the first step for 5G network stepping into the broad range of IoT services that are characterized by the key service requirements. On the other hand, 5G is as well the first generation communication that targets to extend wireless connection to other than human-to-human connections.

The extension of 5G from eMBB to mMTC and URLLC comes from the observation and the demand of the user and application trend. On one hand, high data rate video streams both down to the people (e.g., video streaming downloading) and up to the cloud server (e.g., user share their produced videos to their friends) are expected, and instantaneous and low latency connectivity becomes very vital to the user experiences for including augmented reality (AR) and virtual reality (VR). The user density with such high demand also increases, especially in urban areas; while in rural and/or high mobility cases, a satisfactory end-user experience is also desired by the users. Therefore, the challenging per-user high data rate request combined with high user density and user mobility becomes a driven force for 5G development, which requests significantly enhanced capability for mobile broadband services.

On the other hand, in the future, any object that can benefit from being connected will be connected, through, partially or dominantly, wireless technologies. This trend poses a huge amount of connectivity demand for connecting objects/machines/things in a wide range of applications. For example, driverless cars, enhanced mobile cloud services, real-time traffic control optimization, emergency and disaster response, smart grid, e-health, or efficient industrial communications are what are expected enabled or improved by wireless technologies/connections to just a few named in [1]. By a closer observation of these applications, one can find 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 provide the nature of mMTC and URLLC.

Therefore, 5G puts itself on the target to support diverse usage scenarios and applications including eMBB, mMTC, and URLLC. The following is a first glance on what the three usage scenarios indicates, which comes from [1],

- ***Enhanced Mobile Broadband****:* Mobile Broadband addresses the human-centric use cases for access to multi-media content, services, and data. The demand for mobile broadband will continue to increase, leading to enhanced Mobile Broadband. The enhanced Mobile Broadband usage scenario will come with new application areas and requirements in addition to existing Mobile Broadband applications for improved performance and an increasingly seamless user experience. This usage scenario covers a range of cases, including wide-area coverage and hotspot, which have different requirements. For the hotspot 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. For the wide area coverage case, seamless coverage and medium to high mobility are desired, with much improved user data rate compared to existing data rates. However, the data rate requirement may be relaxed compared to hotspot.
- ***Ultra-reliable and low latency communications****:* This use case has stringent requirements for capabilities such as throughput, latency, and availability. Some examples include wireless control of industrial manufacturing or production processes, remote medical surgery, distribution automation in a smart grid, transportation safety, etc.
- ***Massive machine type communications****:* This use case is characterized by a very large number of connected devices typically transmitting a relatively low volume of non-delay-sensitive data. Devices are required to be low cost, and have a very long battery life.

Additional use cases are expected to emerge, which are currently not foreseen. For future IMT, flexibility will be necessary to adapt to new use cases that come with a wide range of requirements.

In the following, we will first give a survey on the diverse services that are envisioned as 5G use cases, and then investigate the service requirements. Then technical performance requirements are extracted by grouping the similar service requirements to one characterized technical requirement. The importance of the technical requirement will be mapped to different usage scenarios based on the group of services under the specific usage scenario.

1.3.1.2 Survey of Diverse Services Across 5G Usage Scenarios and the Diverse Requirements

There are a broad range of emerging services that are expected to appear for the year 2020 and beyond that are under the scope of the 5G study. Generally, these 5G services are categorized into three groups according to the three usage scenarios elucidated in the last section.