1 Introduction

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1.1 Historical background

The Information and Communications Technology (ICT) sector was born in the twenty-first century out of a consolidation of two major industry sectors of the last century, the telecommunications industry and the computing industry. This book is designated to harness the momentum of the mobile telecommunications industry to a fifth generation of technologies. These technologies will allow completing the consolidation of services, content distribution, communications and computing into a complex distributed environment for connectivity, processing, storage, knowledge and intelligence. This consolidation is responsible for a blurring of roles across the board, with computing and storage being embedded in communication infrastructure, process control being distributed across the Internet and communication functions moving into centralized cloud environments.

1.1.1 Industrial and technological revolution: from steam engines to the Internet

The ICT sector arose out of a natural marriage of telecommunications with the Internet, and is presiding over a tremendous change in the way information and communications services are provisioned and distributed. The massive and widespread adoption of mobile connected devices is further driving deep societal changes with tremendous economic, cultural and technological impact to a society that is becoming more networked and connected. Humanity is going through a phase of a technological revolution that originated with the development of semiconductors and the integrated circuit and continued with the maturing of Information Technology (IT) sector and the development of modern electronic communication in the 1970s and 1980s, respectively. The next frontier in the maturation of the ICT sector is to create an indistinguishable framework for service delivery across a variety of scenarios that span huge variations in demand, including the delivery of personalized media to and from the Internet, incorporating the Internet of Things (IoT) or the Internet of everything into the connected paradigm, and the introduction of security and mobility

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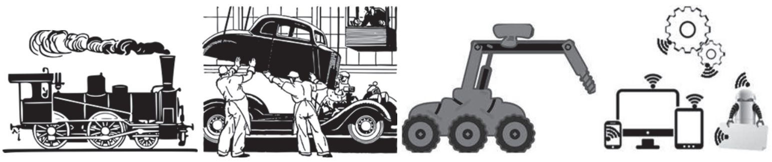

Figure 1.1 The four stages of the Industrial Revolution.

functions as configurable features for any communication scenario. Some would call it the fourth stage of the Industrial Revolution [1].

The four stages of the Industrial Revolution are illustrated in Figure 1.1. The first stage of the Industrial Revolution (approximately 1760–1840) started in England with the introduction of the power loom and the steam engine. As a consequence, the agrarian economy of the eighteenth century underwent rapid transformation within decades to an industrial one, dominated by machinery for manufacturing goods.

The second stage of the Industrial Revolution (approximately 1840–1914) began with the introduction of the Bessemer steel process and culminated in early factory electrification, mass production and the production line. Electrification enabled mass production by dividing the labor into specialized activities on the production line, where a common example is the Ford production model in the car industry.

The third stage of the Industrial Revolution (approximately 1950–2010s) occurred thanks to electronics and IT, and in particular the introduction of Programmable Logic Controllers (PLCs). This allowed further automation of the production process and an increase in productivity.

The fourth stage of the Industrial Revolution may now be seen as the era where a new generation of wireless communications enables pervasive connectivity between machines and objects, which itself enables another leap in industrial automation.

It is expected that the 5th generation of mobile communications (5G) will provide the means to move into exactly this fourth stage of the Industrial Revolution, as it allows the currently human-dominated wireless communications to be extended to an all-connected world of humans and objects. In particular, 5G will have:

- connectivity as a standard for people and things,
- critical and massive machine connectivity,
- new spectrum bands and regulatory regimes,
- mobility and security as network functions,
- integration of content distribution via the Internet,
- processing and storage at the network edge and
- software defined networking and network function virtualization.

1.1.2 Mobile communications generations: from 1G to 4G

Figure 1.2 illustrates a short chronological history of the cellular radio systems from their infancy in the 1970s (i.e. 1G, the first generation) till the 2020s (i.e. 5G, the fifth

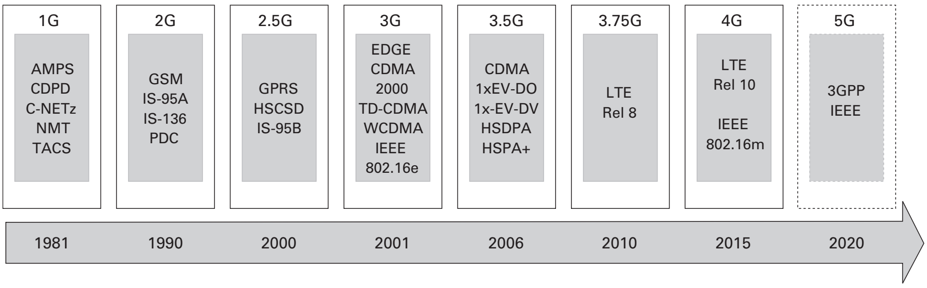

Figure 1.2 Evolution of cellular standards.

generation). The major steps in the evolution of the cellular mobile systems are shown in Figure 1.2 and will be described hereafter.

The first commercial analog mobile communication systems were deployed in the 1950s and 1960s [2], although with low penetration. The year 1981 witnessed the birth of the first commercial deployments of the First Generation (1G) mobile cellular standards such as Nordic Mobile Telephone (NMT) in Nordic countries; C-Netz in Germany, Portugal and South Africa; Total Access Communications System (TACS) in the United Kingdom; and Advanced Mobile Phone System (AMPS) in the Americas. The 1G standards are called the *analog standards* since they utilize analog technology, typically frequency modulated radio signals with a digital signaling channel. The European Conference of Postal and Telecommunications Administrations (CEPT) decided in 1982 to develop a pan-European 2G mobile communication system. This was the starting point of the Global System for Mobile communications (GSM), the dominant 2G standard, which was deployed internationally from 1991. The introduction of 2G was characterized by the adoption of digital transmission and switching technology. Digital communication allowed considerable improvements in voice quality and network capacity, and offered growth in the form of supplementary services and advanced applications such as the Short Message Service (SMS) for storage and forwarding of textual information.

The primary purpose of GSM (i.e. 2G) was to create a common digital voice telephony network that allowed international roaming across Europe. GSM is based on a hybrid Time Division Multiple Access (TDMA)/Frequency Division Multiple Access (FDMA) method, in contrast with 1G systems based only on FDMA [3]. In parallel with GSM, other digital 2G systems were developed around the globe and competed with each other. These other main 2G standards include (1) TIA/EIA-136, also known as the North American TDMA (NA-TDMA) standard, (2) TIA/EIA IS-95A, also known as CDMAOne [4] and (3) Personal Digital Cellular (PDC), used exclusively in Japan. The evolution of 2G, called 2.5G, introduced packet-switched data services in addition to voice and circuit-switched data. The main 2.5G standards, General Packet Radio Service (GPRS) and TIA/EIA-95[1], were extensions of GSM and TIA/EIA IS-95A, respectively. Soon afterwards, GSM was evolved further into the Enhanced

[1] TIA/EIA-95 was a combination of versions TIA/EIA-IS95A and IS-95B.

Data Rates for Global Evolution (EDGE) and its associated packet data component Enhanced General Packet Radio Service (EGPRS), mainly by addition of higher order modulation and coding schemes. GSM/EDGE has continued to evolve and the latest release of the 3GPP standard supports wider bandwidths and carrier aggregation for the air interface.

Shortly after 2G became operational, industrial players were already preparing and discussing the next wireless generation standards. In parallel, the International Telecommunications Union, Radio Communications (ITU-R) developed the requirements for systems that would qualify for the International Mobile Telecommunications 2000 (IMT-2000) classification. In January 1998, CDMA in two variants – Wideband Code Division Multiple Access (WCDMA) and Time Division CDMA (TD-CDMA) – was adopted by the European Telecommunications Standards Institute (ETSI) as a Universal Mobile Telecommunication System (UMTS). UMTS was the major 3G mobile communication system and was one of the first cellular systems that qualified for IMT-2000. Six radio interfaces have been qualified to meet IMT-2000 requirements including three technologies based on CDMA, a version of GSM/EDGE known as UWC-136[2], and two technologies based on OFDMA [5]. Within the framework of the 3rd Generation Partnership Project (3GPP), new specifications were developed, together known as 3G Evolution and illustrated in Figure 1.2 as 3.5G. For this evolution, two Radio Access Network (RAN) approaches and an evolution of the Core Network were suggested.

The first RAN approach was based on the evolution steps in CDMA 2000 within 3GPP2: 1xEV-DO and 1xEV-DV.

The second RAN approach was High Speed Packet Access (HSPA). HSPA was a combination of High Speed Downlink Packet Access (HSDPA), added in 3GPP Release 5, and High Speed Uplink Packet Access (HSUPA), added in 3GPP Release 6 [6]. Both initially enhanced the packet data rate, to 14.6 Mbps in the downlink and to 5.76 Mbps in the uplink, and quickly evolved to handle higher data rates with the introduction of MIMO. HSPA was based on WCDMA and is completely backward compatible with WCDMA. While CDMA 1xEV-DO started deployment in 2003, HSPA and CDMA 1xEV-DV entered into service in 2006.

All 3GPP standards follow the philosophy of adding new features while still maintaining backward compatibility. This has been further applied in an evolution of HSPA known as HSPA+, which supports carrier aggregation for higher peak data rates without affecting existing terminals in the market.

The second UMTS evolution, commercially accepted as 4G, is called Long Term Evolution (LTE) [7][8], and is composed of a new air interface based on Orthogonal Frequency Division Multiple Access (OFDMA) and a new architecture and Core Network (CN) called the System Architecture Evolution/Evolved Packet Core (SAE/EPC). LTE is not backward compatible with UMTS and was developed in anticipation of

[2] Universal Wireless Communications-136 was an evolution of NA-TDMA to integrate GSM-EDGE. It was never deployed as specified by the ITU-R and was abandoned in favor of the 3GPP specification of GSM/EDGE.

higher spectrum block allocations than UMTS during World Radio Conference (WRC) 2007. The standard was also designed to operate with component frequency carriers that are very flexible in arrangement, and supports carriers from 1.4 MHz in width to 20 MHz.

The LTE standard offered significant improvements in capacity and was designed to transition cellular networks away from circuit-switched functionality, which provided a major cost reduction from previous generations. At the end of 2007, the first LTE specifications were approved in 3GPP as LTE Release 8. The LTE Release 8 system has peak data rates of approximately 326 Mbps, increased spectral efficiency and significantly shorter latency (down to 20 ms) than previous systems. Simultaneously, the ITU-R was developing the requirements for IMT-Advanced, a successor to IMT-2000, and nominally the definition of the fourth generation. LTE Release 8 did not comply with IMT-Advanced requirements and was initially considered a precursor to 4G technology. Although this statement was subsequently relaxed in common parlance and LTE is uniformly accepted as 4G, 3GPP LTE Release 10 and IEEE 802.16 m (deployed as WiMAX) were technically the first air interfaces developed to fulfill IMT-Advanced requirements. Despite being an approved 4G technology, WiMAX has had difficulties in gaining widespread acceptance and is being supplanted by LTE. LTE Release 10 added several technical features, such as higher order MIMO and carrier aggregation that improved capacity and throughput of Release 8. Carrier aggregation up to 100 MHz of total bandwidth allows an increase of the peak data rate to a maximum of 3 Gbps in downlink and 1.5 Gbps in uplink. Higher order MIMO configurations up to 8×8 in downlink and 4×4 in the uplink are also involved in the performance improvement.

3GPP standardization of LTE (i.e. Release 11 to Release 13) continues and is expected to proceed to Release 13 and beyond. LTE Release 11 refined some of the LTE Release 10 capabilities, by enhancing carrier aggregation, relaying and interference cancellation. New frequency bands were added, and the use of coordinated multipoint transmission and reception (CoMP) was defined. LTE Release 12, which was concluded in March 2015, added several features to improve the support of heterogeneous networks, even higher order MIMO, and aggregation between Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) carriers. Several features for the offloading of the backhaul and core networks were also defined. Further, in LTE Releases 12 and 13, new solutions (known as LTE-M and Narrow-Band IoT (NB-IoT)) were introduced in order to support massive Machine Type Communication (MTC) devices such as sensors and actuators [9] [10]. These solutions provided improvements in terms of extended coverage, longer battery life, and reduced cost. Release 13 also targets extreme broadband data rates using carrier aggregation of up to 32 carriers.

The cellular global mobile market was about 7.49 billion subscribers [11] by mid-2015, where the GSM/EDGE family including EGPRS for data connectivity is the dominant Radio Access Network (RAN) in use. GSM has a global market share of more than 57% (corresponding to 4.26 billion subscribers), is well beyond peak use and is currently in decline. On the other hand, the number of 3G subscribers including HSPA has risen since 2010 to 1.94 billion subscribers, which represents 26% of the market share. The Ericsson Mobility Report projects that WCDMA/

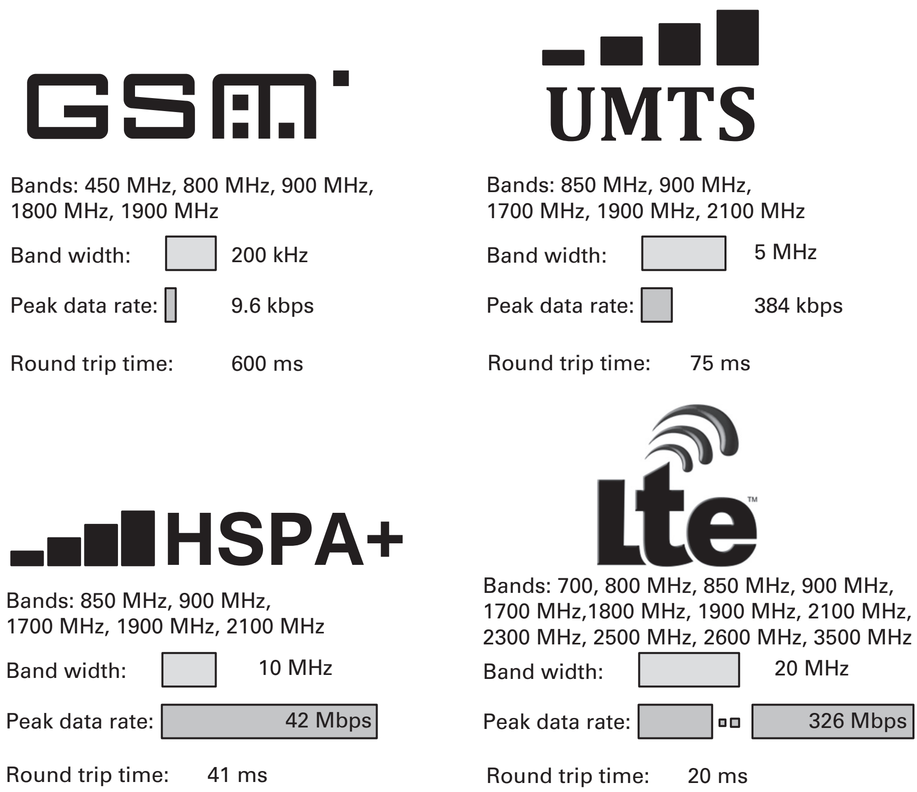

Figure 1.3 Main characteristics of 3GPP/ETSI standards.

HSPA subscriptions will peak by 2020, and will decrease past that point [12]. The dominant 4G standard, LTE, captured around 910 million subscribers (or 12% of the total market) by the end of 2015 and is expected to reach 4.1 billion subscriptions by 2021 [12], hence making it the largest mobile technology. Figure 1.3 illustrates the main features of the 3GPP standards now in the market, highlighting the trend toward widespread use of spectrum, higher bandwidths, higher spectral efficiency and lower latency.

1.1.3 From mobile broadband (MBB) to extreme MBB

Extreme Mobile Broadband (xMBB) services will allow 5G to meet the continuing demand for high data rates and high traffic demands in the years beyond 2020.

The widespread increase in video traffic and the interest in virtual reality and ultra-high definition video streaming will create demand for data rates of the order of many Gbps. The introduction of 5G will allow wireless networks to match data rates and use cases that are currently handled by fiber access.

The Tactile Internet will additionally require support of very low delays through the network. This requirement along with the high user data rate requirements places even greater demands on the peak data rates supported by the system.

1.1.4 IoT: relation to 5G

Over the last few years, several terms such as the IoT, Cyber-Physical-Systems (CPS) and Machine-to-Machine (M2M) have been used to describe a key focus area for the ICT sector. These terms are each used with a specific emphasis:

1. IoT, also referred to as the “Internet of Everything”, emphasizes the aspect of the Internet in which all objects (i.e. humans and machines) are uniquely addressable and communicate via a wire or wirelessly via a network [13],
2. CPS refers to the integration of computation and physical processes (such as e.g. sensors, people and physical environments) via a communication network. In particular, the physical processes can then be observed, monitored, controlled and automated in the digital (i.e. cyber) domain. Embedded computing and communication are the two key technical components that enable CPSs. A modern power grid can be seen as an example of CPSs [14].
3. M2M has been used to represent the way in which machines can communicate between themselves.

Digital processors have been embedded at all levels of industrial systems for many years. However, new communication capabilities (e.g. the ones offered by 4G and 5G) will enable the interconnection of many distributed processors and the possibility to move the digital observation and control from a local level to a system-wide and global level. Moreover, when objects are wirelessly connected via the Internet, and computing and storage are distributed in the network, the distinction among CPSs and IoT terms disappears. Hence, mobile and wireless communications are key enablers for the IoT. 5G in particular will enable IoT for new use cases (e.g. requiring low latency and high reliability) and economical sectors where so far mobile communication has been inexistent.

1.2 From ICT to the whole economy

In contrast to previous cellular generations, one of the major objectives of 5G is to meet projected mobile traffic demand and to holistically address the communications needs of most sectors of the economy, including verticals such as those represented by industries. In some of these economic sectors (such as consumer, finance and media) wireless communication has gradually been making inroads since the onset of the century. The years to follow are expected to push mobility and wireless adoption beyond the tipping point, and 5G will create the conditions where wireless connectivity changes from being an interesting feature to a necessity for a huge number of products in these sectors. The necessity of wireless arises due to the potential for data to build up knowledge, for knowledge to become useful information, and for information to enable higher orders of intelligence in various sectors of the society. At the very least, the data generated from various connected devices will lower the cost of delivering services, and at the very most, it will help accelerate all of humanity to degrees of efficient and productive activity that were impossible during the 255 years since the dawn of the modern Industrial Revolution. Improved wireless broadband connectivity will bring a cascade of secondary benefits to the economy and is capable of improving and bettering the lives of people in untold ways. Some of these economy sectors where wireless communication is expected to play a major role are as follows:

- **Agriculture**: Sensors and actuators are becoming more widely used, e.g. in order to measure and communicate soil quality, rainfall, temperature and wind, to monitor how the crops are growing and livestock movements.
- **Automobile**[3]: Wireless communication is interesting for a multitude of applications associated with intelligent transportation, e.g. to enable greater automation of moving vehicles, to provide Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication for information, sensing and safety to prevent collisions, avoid road traffic congestion etc., as well as commercial applications such as media delivery to the vehicle.
- **Construction/Building**: Buildings are being constructed with sensors, actuators, integrated antennas and monitoring devices for energy efficiency, security, occupancy monitoring, asset tracking, etc.
- **Energy/Utilities**: The Smart Grid is affecting all parts of the value chain including exploration, generation and production, trading, monitoring, load control, fault tolerance and consumption of energy. Future systems where consumers also become producers of energy, appliances are connected and perhaps controlled by utilities, and the increase in the numbers of electric cars pose opportunities and challenges for power companies.
- **Finance (including banking)**: Financial activities, such as trading, banking and shopping are performed more and more over wireless links. Consequently, security, fraud detection and analytics are very important components of financial transactions that are improved due to the use of wireless connectivity.
- **Health**: Wireless communication can be used in a variety of ways ranging from the mundane to the complex; these include exercise monitoring, continuous consumer health sensing, medical alerts and health monitoring by health services, wireless connectivity within hospitals and for remote patient monitoring, remote health service delivery, remote surgery, etc.
- **Manufacturing**: Various engineering tasks and process control can be made more efficient, reliable and accurate with wireless communications; the use of 5G for ultra-reliable operation and extreme requirements on latency is interesting for factory cell automation, while massive machine connectivity will increase in the use of wireless communications in manufacturing for robots, autonomous operation of machines, RFIDs and low-power wireless communications for asset management, etc.
- **Media**: Video is a key driver of high bandwidth consumption, and it is expected that 5G will allow excellent user experience for viewing 3D and 4K formats on a mass scale. Today, the user experience for enjoying rich content like high-resolution video is limited to fixed networks and short-range wireless, while access to high-quality

[3] As it is defined herein, the automobile sector overlaps with the transport sector.

music is stressed in crowded areas where users might simultaneously consume unique content. New use cases such as Virtual Reality (VR) or Augmented Reality (AR) are also expected to become popular in mobile or nomadic situations.

- **Public safety**: Police, fire, rescue, ambulance and medical emergency services covered by this category require a high degree of reliability and availability. Just as 4G is being adopted for public safety, 5G radio access will be a very important component of the tools available for security services, law enforcement and emergency personnel to use. The use of SDN and NFV can help the network play a more direct role in public safety functions, such as fighting fires and assisting in earthquake or tsunami disasters, by efficiently managing local service connectivity between responders and from hazards toward the network. The network can also support rescue missions using location services.
- **Retail and consumer**: Wireless communication will continue to play an important role in areas such as retail, travel and leisure, including hospitality.
- **Transport (including logistics)**: Wireless communication is already playing an important role in this respect. This role will even further increase in the future with the advent of 5G. In fact, 5G will improve the infrastructure and communication functionalities in areas such as railway, public transport and transport of goods by terrestrial or maritime means.
- **Additional industries**: Aerospace and defense, basic resources, chemicals, industrial goods and support services will employ wireless communications increasingly in the coming years.

1.3 Rationale of 5G: high data volume, twenty-five billion connected devices and wide requirements

The necessity of wireless connectivity in society is primarily driven by an increased usage of mobile multimedia services, and has led to an exponential increase in mobile and wireless traffic demand and volume. Mobile traffic was first predicted to increase a thousand-fold over the decade 2010–2020 [15]. The figure was later revised to be in the order of 250 times [16]. It is important to note that in the already highly-developed communication societies, e.g. Western Europe and North America, traffic in cellular systems will increase by approximately a factor of 84 over the years 2010–2020 as shown in Figure 1.4.

Further, machine-type applications are becoming important in addition to the human-centric communications that have been dominating the cellular scene so far. In fact, the number of communicating machines was at some point forecasted to be trending toward the number 50 billion by 2020 [17]. That figure has been revised down to 25 billion connected devices based on more recent considerations [12].

The expected uptake of machine-type and human-type wireless communications in many economic sectors and vertical industries will lead to a large and wide diversity of communication characteristics imposing different requirements on mobile and wireless communication systems, e.g. in terms of cost, complexity, energy dissipation, data rate,

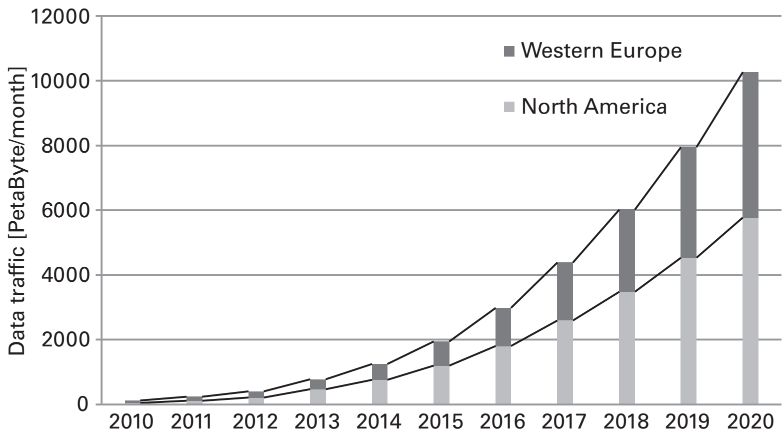

Figure 1.4 Data traffic volume for Western Europe and North America (Copyright 2015 Ericsson).

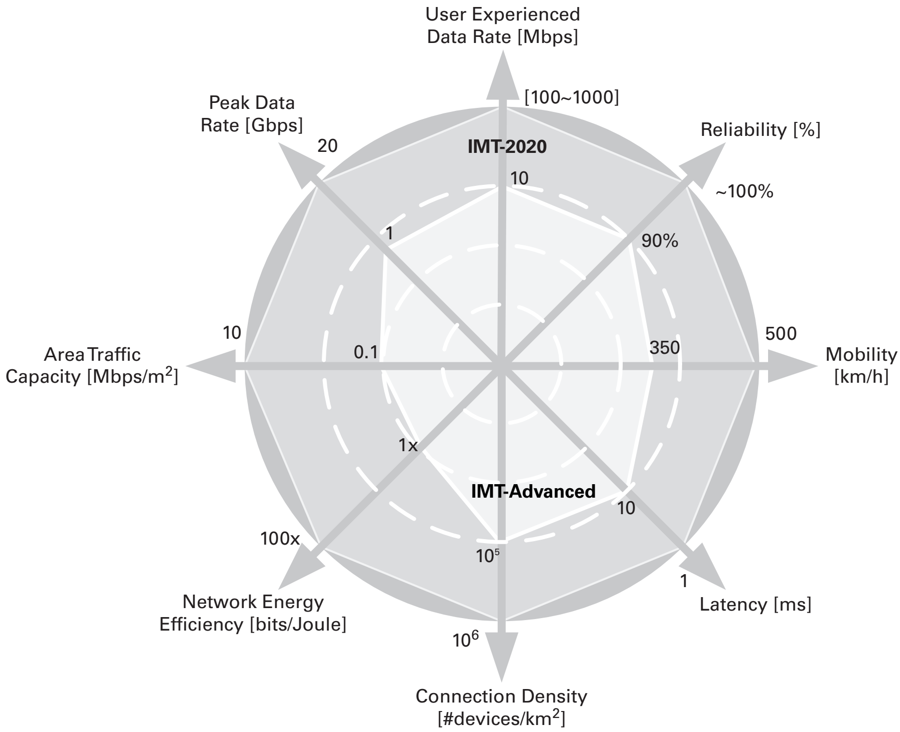

Figure 1.5 Spider diagram for IMT-2020 (i.e. 5G) and IMT-A requirements.

mobility, latency and reliability. For example, the so-called Tactile Internet will require radio latency down to 1 ms [18]. The spider diagram shown in Figure 1.5 is the best way to illustrate the wide range and expansion of the 5G requirements in comparison to prior cellular generations such as IMT-Advanced. In the diagram, the following most relevant key requirements are considered [19]: