

# 1

## Evolution of Mobile Networks

This chapter has focused on the evolution, driving trends, and key requirements of future 6G wireless systems. After reading this chapter, you should be able to:

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- Understand the evolution of mobile networks from 0G to 6G.
  - Understand the present context of 6G development.
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### 1.1 Introduction

While 5G mobile communication networks are deployed worldwide, multitude of new applications and use-cases driven by current trends are already being conceived, which challenges the capabilities of 5G. This has motivated researchers to rethink and work toward the next-generation mobile communication networks “hereafter 6G” [1, 2]. The 6G mobile communication networks are expected to mark a disruptive transformation to the mobile networking paradigm by reaching extreme network capabilities to cater to the demands of the future data-driven society.

So far, mobile networks have evolved through five generations during the last four decades. A new generation of mobile networks emerges every 10 years, packing more technologies and capabilities to empower humans to enhance their work and lifestyle. The precellphone era before the 1980s is marked as the zeroth-generation (0G) of mobile communication networks that provided simple radio communication functionality with devices such as walkie-talkies [3]. The first-generation (1G) introduced publicly and commercially available cellular networks in the 1980s. These networks provided voice communication using analog mobile technology [4]. The second generation (2G) of mobile communication networks marked the transition of mobile networks from analog to digital. It supported basic data services such as short message services in addition to

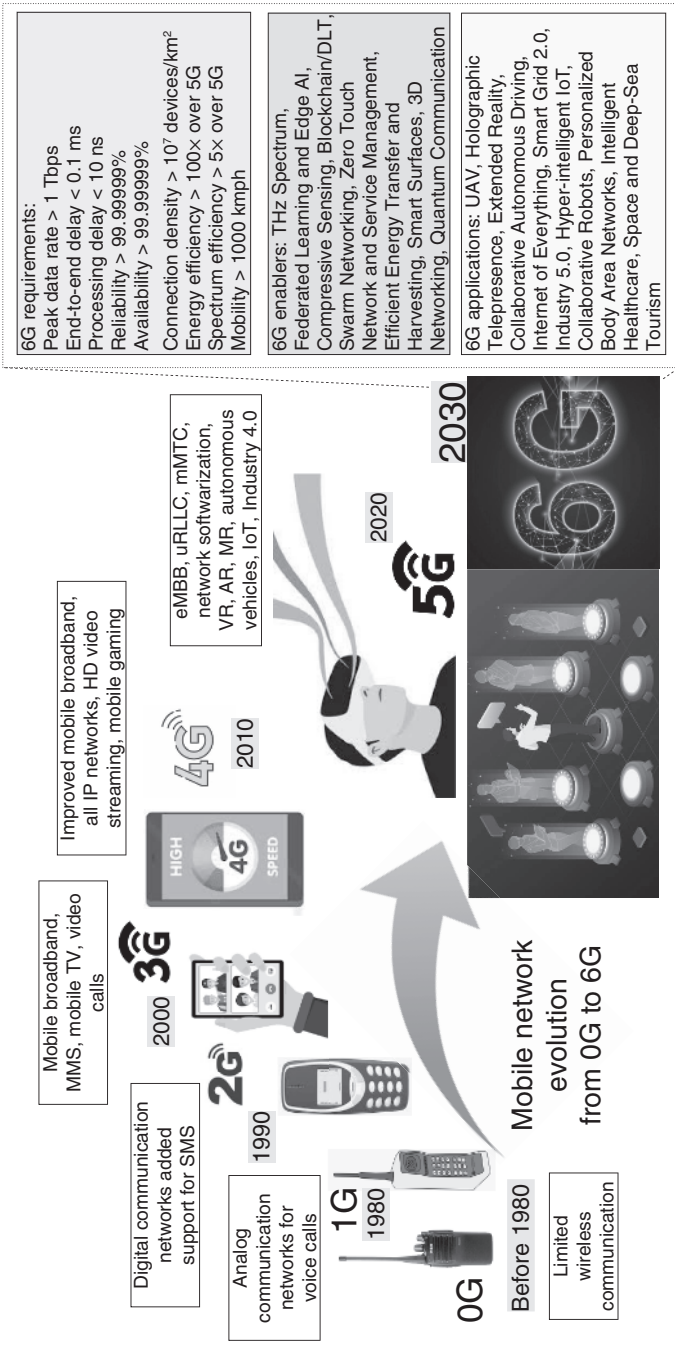
voice communication [5]. The third-generation (3G) introduced improved mobile broadband services and enabled new applications such as multimedia message services, video calls, and mobile TV [6]. Further improved mobile broadband services, all-IP communication, Voice Over IP (VoIP), ultrahigh definition video streaming, and online gaming were introduced in the fourth-generation (4G) [7].

5G mobile communication networks are already being deployed worldwide. 5G supports enhanced Mobile Broadband (eMBB) to deliver peak data rates up to 10 Gbps. Furthermore, ultra Reliable Low Latency Communication (uRLLC) minimizes the delays up to 1 ms, while massive Machine-Type Communication (mMTC) supports over 100× more devices per unit area compared to 4G. The expected network reliability and availability are over 99.999% [8]. Network softwarization is a prominent 5G technology that enables dynamicity, programmability, and abstraction of networks [9]. Capabilities of 5G have enabled novel applications such as virtual reality (VR), augmented reality (AR), mixed reality (MR), autonomous vehicles, Internet of Things (IoT), and Industry 4.0 [10, 11].

Recent developments in communications have introduced many new concepts such as edge intelligence (EI), beyond sub 6 GHz to THz communication, non-orthogonal multiple access (NOMA), large intelligent surfaces (LIS), swarm networks, and self-sustaining networks (SSN) [12, 13]. These concepts are evolving to become full-fledged technologies that can power future generations of communication networks. On the other hand, applications such as holographic telepresence (HT), unmanned aerial vehicles (UAV), extended reality (XR), smart grid 2.0, Industry 5.0, space, and deep-sea tourism are expected to emerge as mainstream applications of future communication networks. However, requirements of these applications such as ultra-high data rates, real-time access to powerful computing resources, extremely low-latency, precision localization and sensing, and extremely high reliability and availability surpass the network capabilities promised by 5G [14, 15]. IoT, which is enabled by 5G, is even growing to become Internet of Everything (IoE) that intends to connect massive numbers of sensors, devices, and cyber-physical systems (CPS) beyond the capabilities of 5G. This has inspired the research community to envision 6G mobile communication networks. 6G is expected to harness the developments of new communication technologies, fully support emerging applications, connect a massive number of devices, and provide real-time access to powerful computational and storage resources.

## 1.2 6G Mobile Communication Networks

6G networks are expected to be more capable, intelligent, reliable, scalable, and power-efficient to satisfy all the expectations that cannot be realized with 5G. 6G is also required to meet any new requirements, such as support for new technologies, applications, and regulations, raised in the coming decade. Figure 1.1 illustrates



**Figure 1.1** Evolution of mobile networks from 0G to 6G. Source: vectorplus/Adobe Stock; hakule/Adobe Stock; ostapenko/123RF; limpix/Shutterstock.

the evolution of mobile networks, elaborating key features of each mobile network generation. Envisaged 6G requirements, vision, enablers, and applications are also highlighted to formulate an overview of the present understanding of 6G.

**Summary:** THz communications are expected to pave the way for Tbps data rate to meet the demands of future applications and have the potential to strengthen backhaul networks. Nevertheless, it suffers from high propagation losses and demands Line of Sight (LoS) for communications. More efforts are required to understand the behavior of THz signals and better channel models are required.

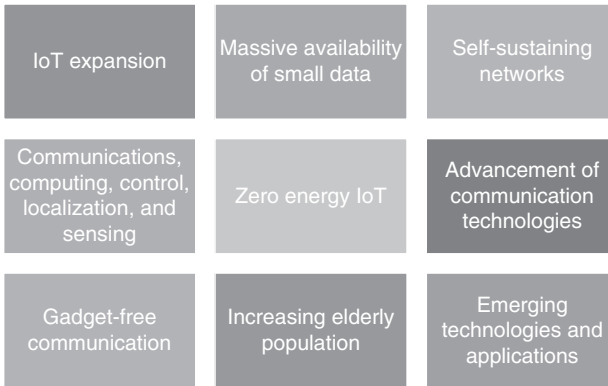
### 1.2.1 6G as Envisioned Today

6G mobile communication networks, as envisioned today, are expected to provide extreme peak data rates over 1 Tbps. The end-to-end delays will be imperceptible and lie even beneath 0.1 ms. 6G networks will provide access to powerful edge intelligence that has processing delays falling below 10 ns. Network availability and reliability are expected to go beyond 99.99999%. An extremely high connection density of over  $10^7$  devices/km<sup>2</sup> is expected to be supported to facilitate IoE. The spectrum efficiency of 6G will be over 5× than 5G, while support for extreme mobility up to 1000 kmph is expected [12].

It is envisioned that the evolution of 6G will focus around a myriad of new requirements such as Further enhanced Mobile Broadband (FeMBB), ultra-massive Machine-Type Communication (umMTC), Mobile BroadBand and Low-Latency (MBBLL), and massive Low-Latency Machine Type communication (mLLMT). These requirements will be enabled through emerging technologies such as THz spectrum, federated learning (FL), edge artificial intelligence (AI), compressive sensing (CS), blockchain/distributed ledger technologies (DLT), and 3D networking. Moreover, 6G will facilitate emerging applications such as UAVs, HT, IoE, Industry 5.0, and collaborative autonomous driving. In light of this vision, many new research work and projects are themed toward developing 6G vision, technologies, use cases, applications, and standards [1, 2].

## 1.3 Key Driving Trends Toward 6G

A new generation of mobile communication has emerged every 10 years over the last four decades to cater to society's growing technological and societal needs. This trend is expected to continue, and 6G is seen on the horizon to meet the requirements of the 2030 society [16, 17]. The technologies, trends, requirements, and expectations that force the shift from 5G toward the next generation of



**Figure 1.2** 6G driving trends. Source: [18, 19]/IEEE.

networks are identified as 6G driving trends. These driving trends will shape 6G into the key enabler of a more connected and capable 2030 society.

This chapter discusses the key 6G driving trends elaborating why and how each trend demands a new generation of communication networks. Figure 1.2 illustrates the 6G driving trends that are discussed in this section.

- **Expansion of IoTs:** It is expected that the number of IoT devices in the world will grow up to 24 billion by 2030. Moreover, the revenue related to IoT will hit the market capitalization of US\$ 1.5 trillion by 2030 [20].
- **Massive availability of small data:** Due to the anticipated popularity of 6G-based IoT devices and new 6G-IoT services, 6G networks will trend to generate an increasingly high volume of data. Most of such data will be small, dynamic, and heterogeneous in nature [12, 21].
- **Availability of self-sustained networks:** 6G mobile systems need to be energy self-sustainable, both at the infrastructure side and at the device side, to provide uninterrupted connectivity in every corner of the world. The development of energy harvesting capabilities will extend the life cycle of both network infrastructure devices and end devices such as IoE devices [22, 23].
- **Convergence of communication, sensing, control, localization, and computing:** Development of sensor technologies and direct integration of them with mobile networks accompanied by low-energy communication capabilities will lead to advanced 6G networks [12, 24]. Such a network will be able to provide sensing and localization services in addition to the exciting communication and computing features [12, 24, 25].
- **Zero energy IoT:** Generally, IoT devices will consume significantly more energy for communication than sensing and processing [26]. The development

of ultra-low-power communication mechanisms and efficient energy harvesting mechanisms will lead to self-energy sustainable or zero energy IoT devices [26].

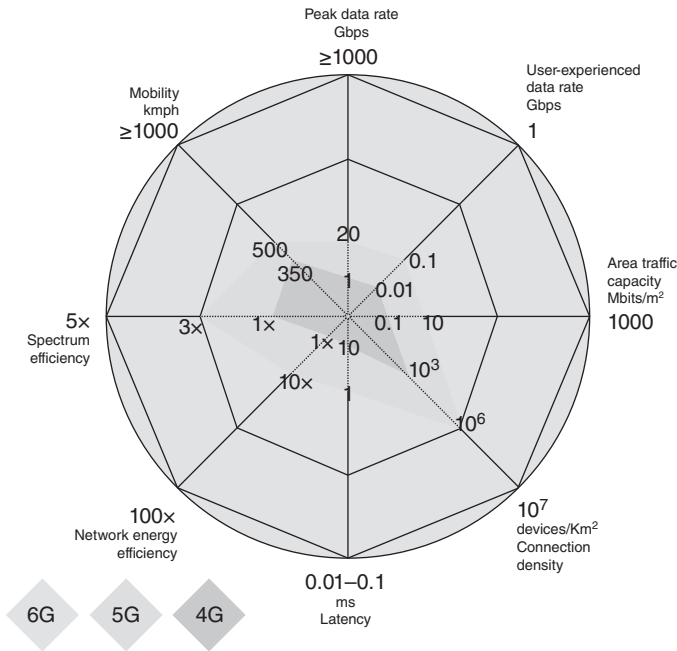
- **More bits, spectrum, and reliability:** The advancement of wireless communication technologies, including coding schemes and antenna technologies, will allow to utilize new spectrum as well as reliably send more information bits over existing wireless channels [12, 16].
- **Gadget-free communication:** The integration of an increasing number of smart and intelligent devices and digital interfaces in the environment will lead to a change from gadget-centric to user-centric or gadget-free communication model. The hyperconnected digital surroundings will form an “omnipotential” atmosphere around the user, providing all the information, tools, and services that a user needs in his or her everyday life [27–29].
- **Increasing elderly population:** Due to factors such as advanced healthcare facilities and the development of new medicines, the world’s older population continues to grow at an unprecedented rate. According to the “An Aging World: 2015” report, nearly 17% (1.6 billion) of the world’s population will be aged 65 and over by 2050 [19].
- **Emergence of new technologies:** By 2030, the world will experience new technological advancements such as stand-alone cars, AI-powered automated devices, smart clothes, printed bodies in 3D, humanoid robots, smart grid 2.0, industry 5.0, and space travel [12, 16]. 6G will be the main underline communication infrastructure to realize these technologies.

## 1.4 6G Requirements/Vision

To realize new applications, 6G networks have to provide extended network capabilities beyond 5G networks. Figure 1.3 depicts such requirements which need to be satisfied by 6G networks to enable future applications.

As adopted from various studies [30–34], 6G networking requirements can be divided into different categories as follows:

- **Further enhanced Mobile Broadband (FeMBB):** The mobile broadband speed has to be further improved beyond the limits of 5G and provide the peak data rate at Terabits per second (Tbps) level. Moreover, the user-experienced data rate should also be improved up to Gigabits per second (Gbps) level [35].
- **Ultra-massive Machine-Type Communication (umMTC):** Connection density will further increase in 6G due to the popularity of IoT devices and the



**Figure 1.3** 6G requirements.

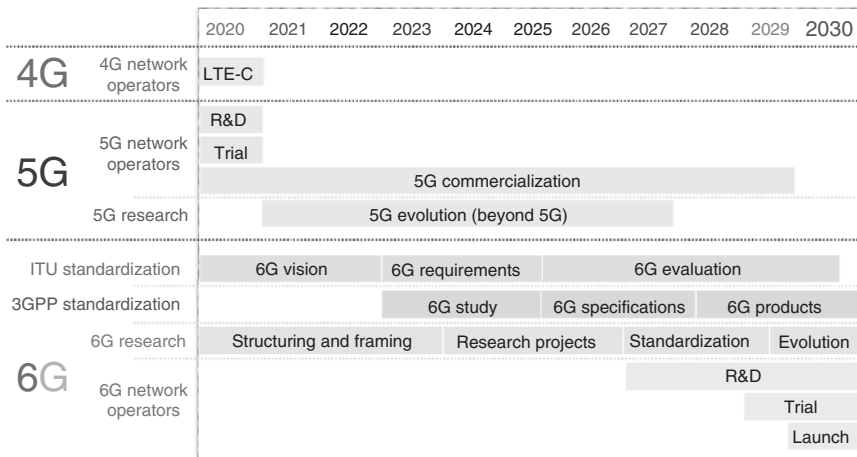
novel concept of IoE. These devices communicate with each other and offer collaborative services in an autonomous manner [36, 37].

- **Enhanced Ultra-Reliable, Low-Latency Communication (ERLLC/eURLLC):** The E2E latency in 6G should be further reduced up to  $\mu\text{s}$  level to enable new high-end real-time 6G applications [17].
- **Extremely Low-Power Communications (ELPC):** The network energy efficiency of 6G will be improved by 10x than 5G and 100x than 4G. It will enable extremely low-power communication channels for resource constrained IoT devices [17, 38].
- **Long-Distance High-Mobility Communications (LDHMC):** With the support of fully integrated satellite technologies, 6G will provide communication for extreme places such as space and the deep sea. Moreover, AI-based automated mobility management systems and proactive migration systems will be able to support seamless mobility at speed beyond 1000 kmph [35].
- **High-Spectrum Efficiency:** The spectrum efficiency will be further improved in 6G up to 5 times as in 4G and nearly two times as in 5G networks [17].

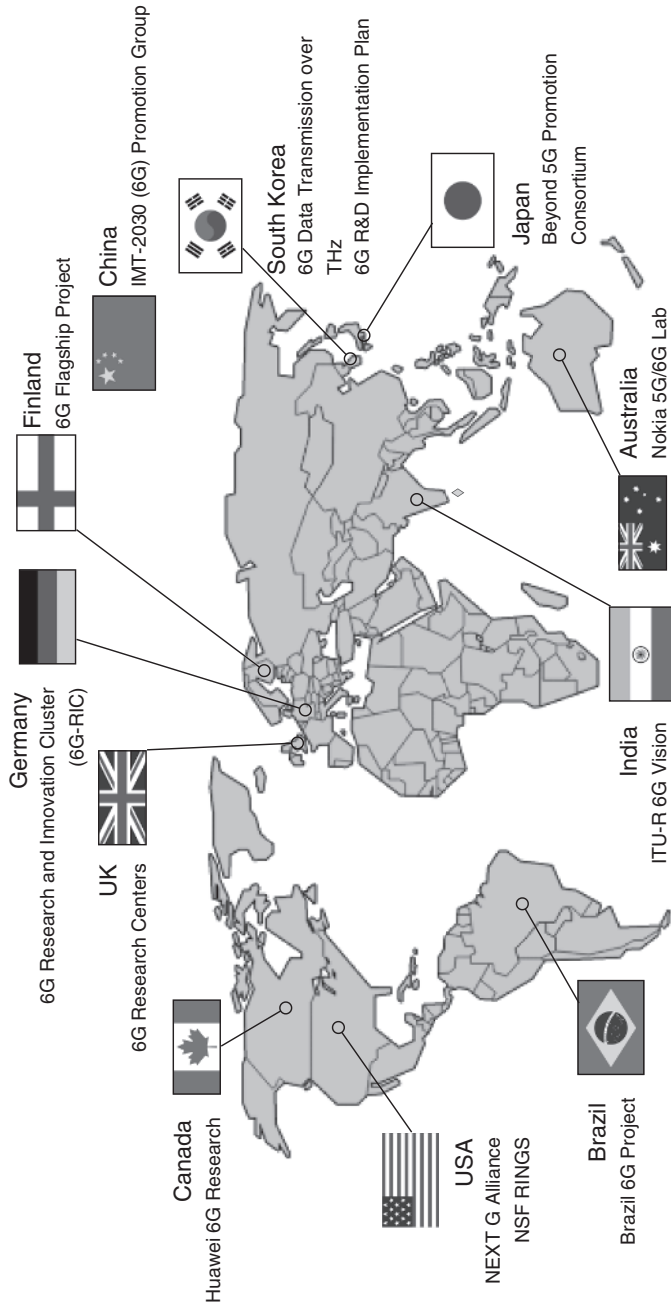
- **High-Area Traffic Capacity:** The exponential growth of IoT will demand the improvement of the area traffic capacity by 100 times than 5G networks. It will lead up to 1 Gbps traffic per square meter in 6G networks.
- **Massive Low-Latency Machine Type (mLLMT):** In 6G, URLLC and mMTC services should be linked, and novel unified solutions are needed to meet the challenge of offering efficient and fast massive connectivity.
- **Mobile broad bandwidth and low-latency (MBLL), massive broad bandwidth machine type (mBBMT), massive, low-latency machine type (mLLMT)**

### 1.4.1 6G Development Timeline

G developments are expected to progress along with the deployment and commercialization of 5G networks, and the final developments of 4G long-term evolution (LTE), being LTE-C, which followed LTE-Advanced and LTE-B [39]. The vision for 6G is envisaged to be framed by 2022–2023 to set forth the 6G requirements and evaluate the 6G development, technologies, standards, etc. Standardization bodies such as the International Telecommunication Union (ITU) and 3rd Generation Partnership Project (3GPP) are expected to develop the specifications to develop 6G by 2026–2027 [39]. Network operators will start 6G research and development (R&D) work by this time to do 6G network trials by 2028–2029, to launch 6G communication networks by 2030 [14, 39–41]. Global 6G development initiatives are illustrated in Figure 1.5, while the expected timeline for 6G development, standardization, and launch is presented in Figure 1.4.



**Figure 1.4** Expected timeline of 6G development, standardization, and launch [14, 39–41].



**Figure 1.5** Global 6G development initiatives.

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