1 Mobile Communications Towards 2030 and Beyond

We are in the midst of a great digital wave that is bringing a continuous stream of innovations, flexibility, and new opportunities to every person, family, car, and industry in many countries, redefining how we live, work, learn, and stay healthy. Today, as the global rollout of 5G picks up pace and unleashes unimaginable possibilities, we are witnessing 5G transform every aspect of our lives, industry, and society. Looking ahead to 2030 and beyond, what might we expect from the next generation of mobile communications?

1.1 Evolution of Mobile Communications

Mobile communication systems have evolved dramatically since the 1980s, with a new generation emerging every 10 years or so. At the same time, the mainstream services provided by mobile networks and the application of new frequency bands usually take two generations – or 20 years – to mature. As shown in Figure 1.1, each new generation brings significant capability improvements compared with its predecessor by introducing new technologies, new design principles, and new architectures in the radio access networks and core networks.

For the 2G and 3G networks, the main drivers were mobile subscriptions primarily focusing on voice communication services. As the penetration rate of mobile phones and usage of voice service reached saturation point, this subscription-based business model began to plateau.

From 3G to 4G, the data service grew rapidly and mobile broadband became the dominant service for 4G. Over the last 10 years, major advancements in mobile communications have had a profound impact on people's way of life. For example, smartphones carrying all kinds of applications have become deeply ingrained in every aspect of the lives of many people. 4G network operators therefore mainly rely on traffic volume rather than subscriptions for revenue, and the growth of traffic consumption per capita drives business growth.

4G has had a dramatic impact on our lives – the technology capabilities it brought have led to numerous innovations in mobile-oriented applications that have revolutionized our daily lives. One primary example of this in China is the shift from using cash to now using online payment methods. Today, young and old alike favor using online payment methods such as AliPay and WeChat Pay, finding it more convenient

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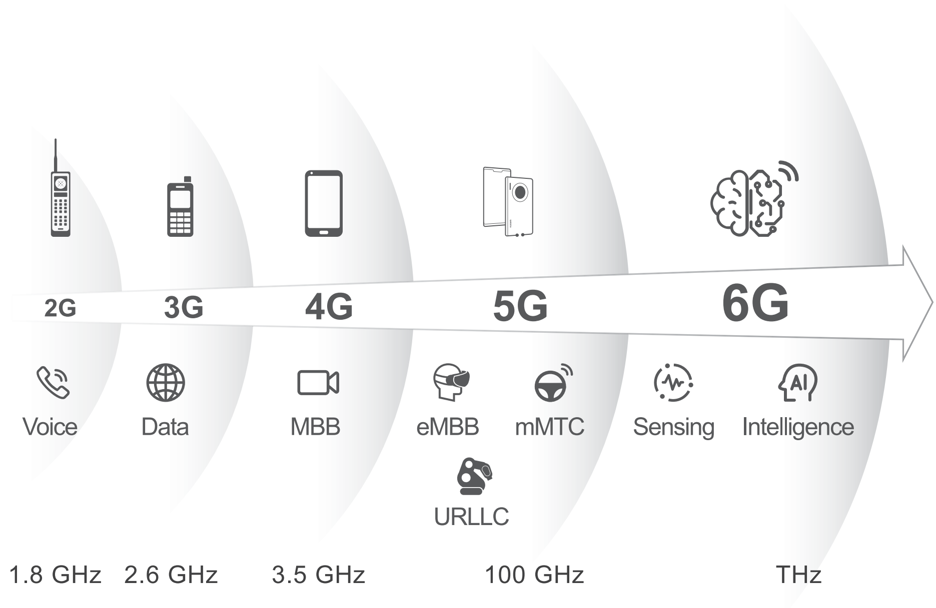

Figure 1.1 Evolution of mobile networks.

to pay for anything from grocery shopping to car parking without carrying cash with them. Another example is the rise of social media. Anyone can now share pictures and videos – effectively becoming a news anchor – to anyone else, anywhere, and at any time from smartphones, speeding up how information is spread.

This trend continues in 5G, as more and more bandwidth-demanding applications continue to emerge. Such applications include high-definition videos and immersive media applications such as augmented reality (AR), virtual reality (VR), and mixed reality (MR). At present, there are approximately 3.8 billion smartphones in use around the world. We expect this number to reach 8 billion by 2025, at which time there will be more than 6.5 billion mobile Internet users with 80% of them having mobile broadband. On top of that, there will be 440 million AR/VR users, and 40% of cars will be connected.

As narrowband Internet of Things (NB-IoT), industry IoT, and vehicle to everything (V2X) have become standardized, mobile networks have shifted some of their focus from connecting people with enhanced mobile broadband (eMBB) to connecting things with ultra-reliable low-latency communication (URLLC) and massive machine type of communication (mMTC). This in turn should enable every business to achieve digitalization for the next wave of economic growth. The 5G commercial deployment initially focused on consumer services, but later releases of 3GPP 5G standardization (e.g., Release 16 and Release 17) have evolved with the aim of driving the maturity of vertical applications such as V2X and industry IoT. To enable different levels of

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autonomous driving and Industry 4.0 across a vast range of businesses and industries, the mobile industry is working closely with verticals at various consortiums such as 5G-ACIA [1] and 5GAA [2] to accelerate the application of mobile technologies. It is expected that level-4 autonomous driving will be available around 2024, and improvements in transportation efficiency are widely anticipated due to the proliferation of V2X. Optimized business process and production efficiency will become the key drivers for future gross domestic product (GDP) growth.

While 5G opens the door for the Internet of Everything (IoE), we predict that 6G – the successor to 5G – will be the platform for connected intelligence, where the mobile network connects vast amounts of intelligent devices and connects them intelligently. The next wave of digitalization is expected to create more innovations that will meet every aspect of our needs. Through artificial intelligence (AI) and machine learning (ML), we will be able to build a real-time connection between the physical and digital worlds, allowing us to capture, retrieve, and access larger amounts of information and knowledge in real time and thus make the connected world a connected intelligence. Furthermore, sensing and distributed computing, together with advanced and integrated non-terrestrial network (NTN) and short-distance wireless communication technologies, will lay the foundation to build intelligent mobile communication networks in the future.

1.2 Key Drivers

As illustrated in Figure 1.2, we predict three key drivers calling for a new generation of connected intelligence. We explain each of these drivers below.

Driver 1: New Applications and Businesses

Today, business revenue is driven by the increase of traffic consumption per subscription. Figure 1.3 shows how the average global mobile traffic per subscription per

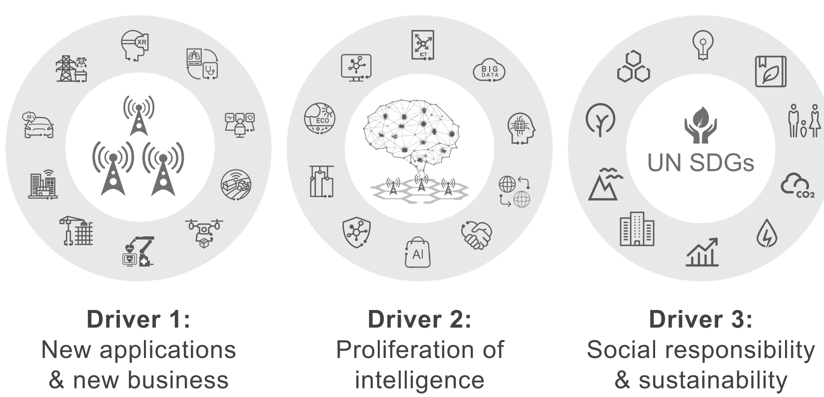

Figure 1.2 Key drivers for 6G.

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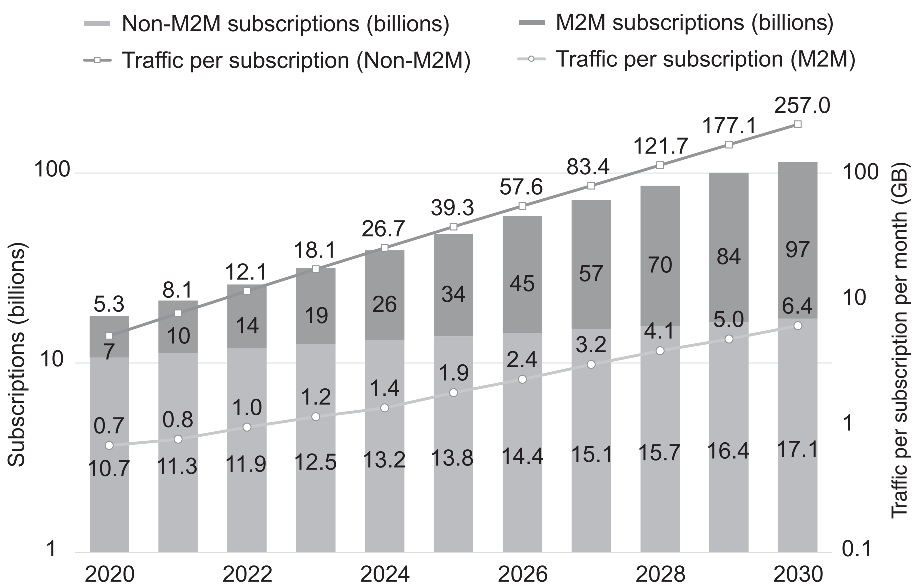

Figure 1.3 Estimation of subscriptions and mobile traffic from 2020 to 2030.

month (solid lines) and the number of subscriptions (bars) are expected to grow from 2020 to 2030 for machine-to-machine (M2M) and non-M2M devices. The data used in the figure were obtained from the ITU-R report M.2370 [3]. From the figure, we can see that the growth of smartphone subscriptions is already saturated in 2020; the compound annual growth rate (CAGR) from 2020 to 2030 is about 6%. In addition, the Global System for Mobile Communications Association (GSMA) expects that the penetration rate of unique mobile subscribers will increase only three percentage points, i.e., from 67% to 70%, from 2019 to 2025 [4]. Yet despite this, the mobile data traffic per MBB subscription is expected to increase 50-fold over the 10-year period, from 5.3 GB per month at 2020 to 257 GB per month at 2030.

A wide range of bandwidth-hungry applications have been supported on the 5G platform, which have increased the traffic volume and driven up the demand for network capacity. In the 6G era, more applications will emerge, and extended reality (XR) cloud services together with haptic feedback and holographic display are likely to become mainstream applications, covering 360 degree VR movies, AR-assisted remote services, virtual 3D educational trips, haptic telemedicine, and remote teleoperation. Huawei's global industry vision (GIV) report [5] predicts that there will be more than 337 million users of head-mounted VR/AR devices by 2025, while more than 10% of enterprises will use AR/VR technologies for business operations, and these numbers are certain to increase by 2030. As cloud XR applications increase both in number and popularity, and as the resolution, size, and refresh rate increase, the bandwidth and latency requirements may exceed what 5G evolution can offer. The exponential increase in the traffic demand per device, together with strict latency and reliability requirements, will become a major challenge for 6G network design in terms of the huge capacity needed. Furthermore, the unlimited data plans that many operators offer have become a key business model and will also contribute to the potential rise of data consumption.

We can also see from Figure 1.3 that there will be about 13 times more M2M devices in 2030 than in 2020, and both enterprise and consumer IoT connections will continue to increase. In its mobile economy report 2020 [4], GSMA predicts that enterprise IoT will overtake consumer IoT by 2024. AI will therefore become an engine for all kinds of automation and will use large amounts of data to convert real-time situational awareness into real-time decision-making. Massive numbers of wideband sensors will be deployed in scenarios such as smart home, smart health, smart car, smart city, smart building, and smart factory to obtain the huge amount of data needed by AI. Big data is foundational to the success of machine learning, and this becomes a major driver for the order of magnitude increase in 6G network throughput. In addition, new capabilities such as networks-as-sensors and non-terrestrial communication will become an integrated part of 6G mobile systems, enabling environmental monitoring and imaging over large areas in real time with an even larger number of sensors.

In addition to this, high-performance industrial IoT applications have demanding requirements on wireless performance in terms of deterministic latency and jitter, and they expect guaranteed availability and reliability. For example, high performance is needed for time-sensitive command and control, as well as multi-robot movement coordination and collaboration. Such use cases also drive the extreme and diverse performance needed for 6G.

Driver 2: Proliferation of Intelligence

In the coming decades, the digital economy will continue to be a major driver of economic growth worldwide, growing much faster than the global economy. In 2019, the digital economy grew 3.5 times faster than the global economy and reached US$15.60 trillion, accounting for 19.7% of the global economy. This is expected to reach 24.3% by 2025. In terms of investment leverage, analysis shows that every $1 increase in digital investment over the past 30 years has led to a $20 increase in GDP, compared to an average of 1 : 3 for non-digital investment [6].

As one of the most dynamic sectors within the information and communications technology (ICT) industry, the mobile industry has had a profound impact on people's lives, helped to mitigate the digital divide, and contributed significantly to society's overall productivity and economic growth. By 2024, mobile technologies and services are expected to generate 4.9% of the global GDP (approaching US$5 trillion), with more industries benefiting from the improvements in productivity and efficiency brought by the increased adoption of mobile services [4].

We believe this trend will continue into 2030 and beyond. In particular, as pervasive intelligence becomes the key enabler of business and economic models in the future, paradigm shifts in radio technology and network architecture will be driven by four critical factors, as illustrated in Figure 1.4.

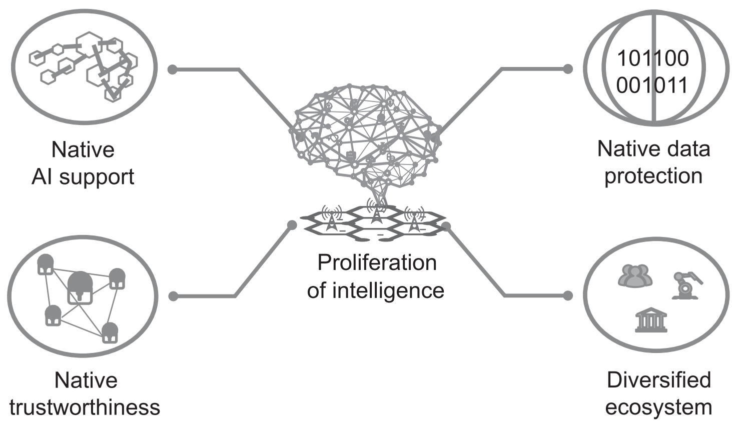

Figure 1.4 Business drivers brought by pervasive intelligence and big data.

- **Native AI support:** Although the core network design in 5G supports intelligence by introducing a new type of network function (i.e., network data analytics), there is limited scope for usage in network operations and management. Instead, 5G delivers AI as an over-the-top (OTT) service. Conversely, for 6G, end-to-end (E2E) mobile communication systems are designed with optimal support for AI and machine learning – not only as a basic functionality, but also for optimal efficiency. From the architecture perspective, running distributed AI at the edge could achieve ultimate performance while also addressing the data ownership concerns of individuals and enterprises as well as meeting regional and national regulatory constraints. "Native" AI support in 6G aims to deliver AI services anywhere and at any time, and will continuously improve system performance and user experience through continual optimization. Consequently, truly pervasive intelligence in combination with deeply converged ICT systems, featuring diverse connectivity, computing, and storage resources at the edge, will become a native trait. The corresponding capabilities (such as algorithms, neural networks, databases, and application programming interface (APIs)) must be integrated into the 6G system as part of the network realization. The 6G network architecture with native AI support will bring "Networked AI," moving away from today's centralized "Cloud AI."
- **Native data protection:** In addition to the security capabilities developed in 5G and earlier generations, privacy will be a critical design requirement and principle for 6G. The protection of privacy in every aspect of 6G networking and data will be essential. On the one hand, the key driver behind this is data ownership and the right to access data, posing a challenge in how the network architecture can ensure privacy protection. On the other hand, native AI requires the capability to process and access data in a distributed manner. Instead of relying on network and application service providers to ensure data protection, we expect that users – which might be people or machines – will be empowered as data subjects with control and

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operation rights. The design of the next-generation system should make privacy-guarantee the top priority instead of only a side feature. Such a design should also ensure the proper rights of data subjects, enable data control and processing, and integrate support for policies like the General Data Protection Regulation (GDPR) in order to establish fundamental guidelines for technology design and usage in the future.

- **Native trustworthiness:** To support a diverse range of use cases and markets, it is essential to have customized, verifiable, and measurable trustworthiness. The nomothetic network ownership and operation for the current and previous generations of networks will evolve into many-parties, many-players, and many-actors. This business driver will promote a trustworthiness architecture that includes many factors. An inclusive multi-lateral trust model will be more vital than the single-trust model. In addition to being future-oriented, the trustworthiness architecture should include security, privacy, resilience, safety, and reliability.
- **Diversified ecosystem:** The three fundamental elements for AI are data, algorithms, and computing. However, individual businesses may not possess full capabilities in these aspects to achieve digital transformation with pervasive intelligence and fast technological innovation. Consequently, it is essential to establish an open, sustainable, and multi-party collaborative ecosystem in order to achieve business success.

Furthermore, as 5G capabilities gradually expand, the vertical wireless market is expected to ramp up throughout the 2020s. Players in both the ICT and operational technology (OT) sectors are exploring how to collaborate in order to generate new sources of revenue. As we approach the 6G era, it would be beneficial if there were a universal ICT framework that could offer an overarching perspective for all industries and thereby accelerate the collaboration and convergence of the ICT and OT sectors. The first wave of 6G commercial use is likely to boost both the consumer and vertical markets.

Driver 3: Social Responsibility and Sustainability

In terms of social responsibility and sustainability, let's take the COVID-19 pandemic as an example. This global crisis has had an impact on almost everyone worldwide, during which time the ICT industry stepped up and played a crucial role in saving human lives. Wireless communication and positioning technologies were used to trace infected patients and monitor the spread of the disease, while minimizing the exposure of medical personnel to it has given rise to significant innovations in 5G for healthcare automation. To limit large gatherings of people while also keeping the economy active, many countries used various remote applications over wireless networks, including applications such as telemedicine, tele-education, telecommuting, industrial automation, and e-commerce. As the mobile industry supported different sectors of the global economy and society during this pandemic, the resulting use cases that emerged from it have contributed to the future technological evolution of the mobile industry.

Mobile networks have the potential to transform business, education, government, healthcare, agriculture, manufacturing, and the environment, as well as the way we

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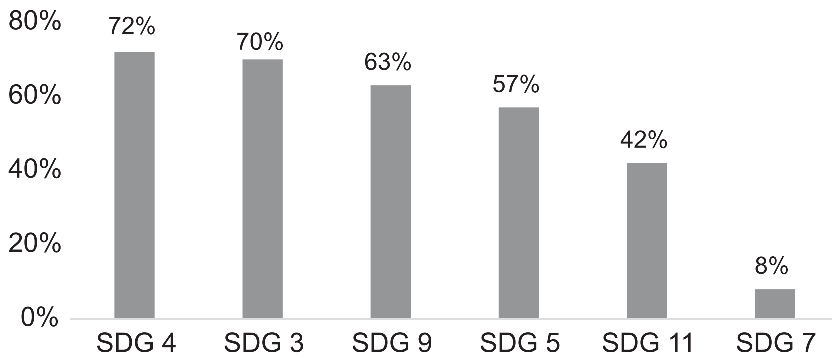

Figure 1.5 Top correlations between individual SDGs and ICT development. From a joint report of Huawei and UN [7]. SDG 4: Quality education; SDG 3: Good health and well-being; SDG 9: Industry, innovation, and infrastructure; SDG 5: Gender equality; SDG 11: Sustainable cities and communities; SDG 7: Affordable and clean energy.

interact with others. They have become one of the key drivers of social evolution and may redefine our very existence. According to the GSMA [4], mobile communication is central to the sustainable development goals (SDGs) set by the United Nations (UN) in 2015 to transform our world, and is a powerful tool for achieving these SDGs. The mobile industry has had a significant impact across all 17 SDGs – an impact that continues to grow, providing a solid foundation for the digital economy and acting as a catalyst for a diverse and innovative range of services.

Huawei and the UN worked together on the ICT SDG Benchmark [7] to measure the degree to which ICT development enables progress on the SDGs in a quantitative manner. The assessment in 2019 showed a strong correlation between ICT maturity and the progress on the SDGs, reaching $R^2 = 0.86$. Among them, as shown in Figure 1.5, SDG 3 (Good health and well-being) and SDG 4 (Quality education) showed the strongest correlation with ICT, signaling the areas where digital technology has the highest potential to accelerate a country's performance.

Regarding environmental sustainability, the evolution of ICTs is critical to achieving SDG 7 (Affordable and clean energy) and SDG 11 (Sustainable cities and communities). The world is becoming increasingly urbanized, with projections showing that 5 billion people will live in cities by 2030 and occupy just 3% of the inhabitable land while accounting for 60%–80% of energy consumption worldwide [8]. ICTs will become more carbon neutral as they achieve higher and higher energy efficiency per bit, and ICT-enabled solutions (e.g., smart grids, smart logistics, and smart industry) will help transform the world towards a more sustainable and energy-efficient future [9].

As of the year 2020, about 90% of people worldwide have access to 3G or 4G networks. For the remaining 10%, both 5G and 6G will aim to connect them by using technologies such as satellite communications. As an example, 5G has already attempted to integrate non-terrestrial access technologies into 5G New Radio (NR) technologies, while ambitious plans for very low earth orbit (VLEO) – constella-

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tions of tens of thousands of VLEO satellites – might come to fruition in the 6G era. Services, applications, and contents enabled by mobile networks are helping to expand financial and social inclusion, while emerging technologies such as IoT, big data, AI, and machine learning are being integrated into the network infrastructure, demonstrating their potential to significantly transform society and the environment. The strong correlations between ICT and SDGs mean that we must consider all aspects of the SDGs when designing 6G communication systems and networks.

1.3 Overall Vision

Mobile communication, over the span of only 40 years, has completely revolutionized the world. Today, we depend heavily on wireless connectivity for both work and life; it has become a key enabler for the digital transformation of every business. As 5G – the current generation of wireless connectivity – starts to take hold, everything, in addition to every person, will be connected; with this hyper-connectivity, we will be able to automate every aspect of society. Moreover, the momentum for wireless innovations is accelerating. As was pointed out in [10]. *Science, the endless frontier*, wireless is indeed the endless frontier.

As wireless technology innovations continue over the next 10 years, the rise of machine-learning-based AI and the creation of digital twins (i.e., representing the physical world as a cyber one) are the two major catalysts fueling more technology breakthroughs. The resulting 6G will be a game-changer in terms of both the economy and society – it will lay a solid foundation for the future Intelligence of Everything.

6G will be the next generation of wireless communication, transiting from an era of connected people and connected things to one of connected intelligence. As society moves towards the Intelligence of Everything, 6G will be the key to proliferating AI, delivering intelligence to every person, home, car, and business.

Functioning like a distributed neural network with communication links, 6G will fuse the physical and cyber worlds. It will not be simply a pipe carrying bits, but rather a network for everything sensed, everything connected, and everything intelligent. As such, 6G will be a network of sensors and machine learning, where data centers will become neural centers with machine learning spread over the entire network. This is the blueprint of the cyber world for the future Intelligence of Everything.

6G will be a key enabler in achieving the full-scale digital transformation of all vertical businesses. Offering extreme performance, such as multi-Tbit/s data rates, sub-millisecond latency, and seven nines (99.99999%) reliability, 6G will realize major improvements in terms of key performance indicators (KPIs) – more than an order of magnitude higher in some cases – compared with 5G. It will provide universal, high-performance connectivity comparable with fibers in terms of speed and reliability, except that it will do so wirelessly. Free from functional and performance limitations, 6G will be a generic platform that supports the creation of any service and any application, reaching an ultimate "connectivity supremacy"!

The disruptive technologies used in 6G – along with major innovations – will set it apart from previous generations. Here we describe just some of 6G's key highlights, which will have a profound effect for decades to come.

- 6G will be designed from the ground up with native AI capabilities, and the network architecture will include machine learning capabilities, in particular, distributed machine learning. To put it simply, 6G is a network designed to support AI, or a network for AI, where many network elements will perform AI and machine learning functions.
- Wireless sensing, a natural characteristic of radio wave propagation, will be a key disruptive technology in 6G, using radio transmission and echoes to detect (or sense) the physical world. Previous generations of wireless systems primarily carried information over radio waves. However, in order to support AI and machine learning, we need to collect extremely large amounts of data from the physical world; 6G radios can function as sensors for this purpose. In particular, by using higher frequencies, such as millimeter wave (mmWave) and the terahertz (THz) spectrum, 6G will enable high-resolution sensing.
- The integration of VLEO satellite constellations with terrestrial networks will also be a major differentiator in 6G. Densely deployed small satellites will enable a "wireless network in the sky" for full-earth coverage. This has been made economically viable with the breakthroughs achieved by Space-X in advanced satellite launching technologies, significantly lowering the cost to construct massive satellite constellations. This novel non-terrestrial wireless infrastructure will be complementary to the existing terrestrial-based cellular system with a completely integrated design, which will be a key enabler for 6G.
- The network architecture used in 6G will differ significantly from earlier generations. 6G centers on data and the intelligence and knowledge derived from it. The network architecture will be designed to enable native trustworthiness with advances in security technologies, privacy preservation, and data governance. This will require a basic network re-architecture in 6G to reflect the Intelligence of Everything. In addition, 6G will employ new data ownership, trust models, and security designs resistant to quantum-computing-based attacks.
- Sustainability is a central topic for 6G, particularly in terms of energy consumption across the entire network and associated ICT infrastructure and devices. The design of 6G must meet stringent requirements in this regard. Specifically, the total power consumption of 6G infrastructure must be much lower than previous generations, and realizing an E2E architecture that is both sustainable and energy-efficient must be prioritized. As a global ICT infrastructure, 6G will be designed with the ultimate goal of social, environmental, and economic sustainability. The future of intelligence must align with our common goal of making our planet a better place in which to live.

In summary, *shifting from connected people, connected things to connected intelligence is the driving force for 6G*. It is the guiding principle behind 6G use cases, network designs, and technologies. Artificial intelligence, the fusion of the physical

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and cyber worlds, and connectivity supremacy are the new pillars on which we aim to build a society with Intelligence of Everything.

We envisage that 6G technologies will offer the following six new capabilities in order to address the potential challenges faced in the 6G era:

6G will reach the ultimate level of connectivity supremacy; employing all radio frequencies up to terahertz or even visible light.

Traffic growth typically drives the need for additional wireless spectrum, while the cellular network infrastructure favors the lower-frequency spectrum in order to achieve ubiquitous coverage. As several generations of wireless networks have evolved, increasing amounts of spectra have been allocated for network upgrades. In addition to the mmWave spectrum, 6G will utilize terahertz or even visible light for the first time, meaning that all potential spectra will be employed to achieve extreme connectivity. Emerging coverage solutions such as VLEO satellites, which provide new coverage infrastructure, and on-demand high-altitude platform stations (HAPSs), which provide temporary coverage infrastructure, require innovative approaches to aggregate the available spectra for 6G capacity and network solutions. This includes defining spectrum ownership and usage models such as sharing, flexible spectrum allocation, and duplexing. In this way, 6G will offer near-infinite capacity with an unprecedented wireless connection speed. With such capability, the new 6G air interface can unify eMBB, URLLC, and mMTC physical-layer technologies, as capacity and latency will no longer be bottlenecks hampering the design of a truly customized wireless connection for every user, service, application, and scenario.

6G will support AI natively, connecting intelligent things and connecting things intelligently.

One of the primary objectives for 6G is to support ubiquitous AI, where 6G will be an E2E system designed to support AI-based services and applications. This capability is neither an add-on nor an over-the-top (OTT) feature; instead, the 6G system itself should be the most efficient platform for AI. However, this presents new challenges in terms of realizing minimal costs for both communication and computation, each of which is a KPI for future study. For minimal communication costs, it is necessary to design a 6G system capable of transferring massive amounts of big data for AI training while using minimal capacity. In terms of minimizing computation costs, it is necessary to optimally distribute computing resources across the networks at strategic locations where we can best leverage mobile edge computing. To support machine learning, 6G will need to enable the collection of massive data from the physical world in order to create a cyber world. This is a significant increase in data, posing a major challenge for 6G. As such, achieving effective compression of training data based on information and learning theories will be a new and essential area of research. Another challenge is reducing the computational load involved in AI training by using collaborative learning. At the network level, data splitting and model splitting will be incorporated into the 6G architecture, where the distributed and federated learning will not only be used to optimize the computing resource, the local

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learning, and the global learning, but also to conform to new data local governance requirements. In terms of the network architecture, the core network functions will be pushed towards a deep-edge network, while software cloudification will shift towards machine learning. In addition, the 6G RAN will shift from downlink-centric radio access to uplink-centric radio access, because the massive training data involved in machine learning require significantly higher throughput in the uplink. Moreover, the 6G air interface can be designed with new machine learning capabilities to achieve intelligent communication.

6G will be networked AI, redefining networking and computing.

AI will be ubiquitous in 6G and drive new architectures for networking and computing. For example, the cloud-based data centers in use today will evolve into native AI neural centers. This involves a shift from CPU-based computing to graphics processing unit (GPU)-based computing. In most cases, AI-specific computing hardware must be co-designed and optimized with the AI algorithms. However, the rise of AI brings a significant challenge in terms of computing. On average, the human brain achieves data rates of 20,000 Tbit/s and can store 200 TB of information while consuming only 20 watts. Conversely, today, the computing power of AI is doubling every two months, far in excess of Moore's law. To achieve the same capabilities as the human brain, a neural center will consume 1000 times more power than the human brain at a point in time near the end of Moore's law. In order for neural centers to replace data centers and fully leverage the potential of AI, it is imperative to use significantly advanced machine learning technologies that facilitate sustainable AI-based 6G [11]. A standardized approach to implementing a neural center computing architecture and software orchestration is critical to enabling the 6G network to be an open platform and an open ecosystem.

6G will function as a networked sensor, enabling the fusion of cyber, physical, and biological worlds.

Sensing is a new and foundational feature for 6G – it is a new channel through which we can link the physical and biological worlds to a cyber world. In order to create a parallel cyber universe that is a true replica of the physical one, specifically, a digital twin, we need real-time sensing. 6G radio wave will be used to realize sensing functionality across all radio access nodes and devices, including base stations and mobile devices. The sensing data collected by the network and devices can be used for two purposes: to enhance communications, especially for beam-based mmWave and THz frequency bands; and to facilitate machine learning and AI. In both cases, sensing data contain real-time information and knowledge about the physical and biological worlds. As such, we can consider 6G to be a networked sensor, differing significantly compared with previous generations of wireless systems, which simply transport information. Network- and device-based sensing can realize global and local sensing, respectively. With such functionality, 6G will bring real-time AI and machine learning to the next level.

6G with integrated terrestrial and non-terrestrial networks will deliver complete full-earth coverage, eliminating digital divide.

Integrating non-terrestrial networks, especially VLEO satellite mega constellations, into 6G is a very attractive feature. A VLEO satellite system, in addition to delivering full-earth coverage, offers a number of new capabilities and advantages. For example, it eliminates the issue with communication latency inherent in conventional geostationary earth orbit (GEO) and medium earth orbit (MEO) satellite systems. It can also provide coverage to areas uncovered by terrestrial networks, offering complementary radio access. One of the VLEO satellite system's unique advantages is that it provides a low-latency global communication link, which is essential for mission-critical applications such as frequent stock trading. VLEO satellite systems can also provide more accurate positioning, which is critical for autonomous driving and important for earth sensing and imaging. In addition to satellite communications, new radio nodes such as drones, unmanned aerial vehicles (UAVs), and HAPSs will be an integral part of 6G, functioning as either mobile terminals or temporary infrastructure nodes.

6G will support a prosumer-centric instead of operator-centric network architecture, embracing an inclusive open ecosystem.

6G will bring about a paradigm shift as it drives economic and social changes with advances in virtualization and AI. 6G networks will have intelligence at their foundation, enabling a participatory approach to networking and service provisioning. This will redefine the intelligent connectivity infrastructure as a dynamic pool consisting of all participating users' resources. It is a radical paradigm shift from the conventional operator-centric view to an inclusive prosumer-centric view (a prosumer both produces and consumes a particular commodity). Through a collaborative model bringing together many networks, key aspects such as multi-lateral ownership, data ownership and privacy, and trust models of involved players must be designed as built-in features rather than built-after ones. Furthermore, in order to achieve local data governance and network sovereignty, 6G will adopt new trust-model and security technologies.

In an inclusive prosumer-centric model, every system participant can both contribute and consume resources and services. Employing AI and machine learning technologies, 6G networks will be fully autonomous, requiring no manual intervention. In this regard, 6G networks will be tailored rather than proprietary, giving rise to the concept of "my network."

1.3.1 Key Technology Trends

Based on the overall vision of 6G discussed in the previous section, we can conclude the following points.

- 6G will enhance human communication, providing the ultimate immersive experience with true human perception anywhere.

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- 6G will enable novel machine communication, redefining intelligent communication for efficient machine-oriented access and connectivity. 6G will fully integrate both machine learning and AI.
- 6G will expand beyond just communication. It will integrate new functions such as sensing and computing, enabling new services and leveraging enhanced knowledge of the environment for machine learning.
- 6G will usher in a new and distinctive wireless generation to support the future Intelligence of Everything. As part of this, AI, trustworthiness, and energy efficiency will be native features of 6G.

In what follows, we discuss six major technology trends.

Trend 1 – New spectrum up to THz and optical wireless communications for extremely high data rates.

To enable new applications such as AR/VR/MR and holographic communications, ultra-high data rates up to tens of Tbit/s are needed. The mmWave sub-THz and bands will be the key spectrum in 6G cellular networks, while the lower-THz band (0.3–1.0 THz) will be a prime candidate for short-distance transmission, e.g., for indoor or for device-to-device (D2D) communication. The THz band offers ultra-wide bandwidth exceeding tens of GHz. The THz will enable a wide range of data-hungry and delay-sensitive applications; in addition to this the THz can be used for wireless sensing.

THz communications is a new wireless technology that involves numerous challenges. Research is currently exploring the design of high-power devices, new materials for antennas, radio frequency power transistors, THz transceiver on-die architecture, channel modeling, and array signal processing. Whether THz technology is successfully adopted in 6G depends on the engineering breakthroughs in THz-related components such as electronic, photonic, and hybrid transceivers and on-die antenna arrays.

Communication through visible light is a potential radiation-free transmission technology that enables connectivity without significant electromagnetic field exposure. However, a large-scale micro-LED array technology will be required to attain data rates reaching tens of Tbit/s for short-distance communications with low power consumption, small form factors, and low-cost devices. In addition, visible light communication (VLC) can access large amounts of unlicensed spectrum, but whether VLC can be successfully utilized in 6G hinges on several challenges in terms of uplink transmission, mobility management, and high-performance transceivers.

Trend 2 – Integrated sensing and communication (ISAC) for new services and enhanced wireless communications.

Traditionally, sensing is a stand-alone function with a set of dedicated devices and equipment, such as radar, lidar, computed tomography (CT), and magnetic resonance imaging (MRI). Mobile phone positioning in mobile systems, assisted by air interface signaling and device-based measurements, is an elementary sensing-like capability. However, by utilizing the mmWave and THz bands, which offer wider bandwidth and smaller wavelength, 6G will make it possible to integrate the sensing function into the communication system, which is especially relevant for the mmWave and terahertz bands. In a full ISAC system, the sensing and communication functions will complement each other to offer the following key benefits.

- **Cellular as a sensor:** Communication signals will be used for new sensing functions, such as high-accuracy localization, gesture and activity recognition, object detection and tracking, imaging, and environmental object reconstruction.
- **Sensing-assisted communication:** Sensing assists and improves quality of service (QoS) and performance for communication, including path selection, channel prediction, and beam alignment.

Integrated sensing and communications make it possible for sensing services in 6G to move beyond simple positioning. Instead, they will be new services that offer additional sensing features with enhanced accuracy (which describes the difference between sensed values and real values in range, angle, velocity, etc.) and sensing resolution (which describes the capability to separate between multiple objects in range, angle, velocity, etc.). Chapter 3 discusses this in greater depth.

Compared with traditional radar sensing, 6G sensing, utilizing the broadband spectrum and larger antenna arrays, will enable technological innovations such as large-scale cooperation between base stations and user devices, joint design of communication and sensing waveforms, advanced techniques for interference cancellation, and sensing-assisted AI. Sensing will potentially be one of the most disruptive services available in 6G, upon which numerous real-time machine learning and AI applications can be created.

A much higher sensing accuracy and resolution can be achieved with THz sensing, due to the ultra-wide bandwidth. Given the range of wavelength and properties of molecular vibration, THz sensing can perform spectrogram analysis to identify the constituent parts of different types of food, medicine, and air pollution. Due to its compact form factor and non-ionizing safety, THz sensing can be integrated into mobile devices and even wearables to identify the number of calories in food and help detect hidden objects. 6G sensing devices will become a gateway for realizing numerous innovative AI applications.

Trend 3 – AI as both a service and a feature in the 6G communication system to intelligently connect intelligent devices.

The key design challenge in 6G is to combine wireless and AI technologies at the beginning rather than designing a wireless system first and then applying AI. Leveraging AI to enhance the 6G wireless system creates opportunities for post-Shannon communications theory research and innovations in wireless technologies.

There are two types of designs involved in 6G: (1) *AI for network* uses AI applications as tools to optimize the network. (2) *Network for AI* tailors a network to support and optimize AI applications. The network also assists in providing AI functionality or even performing such functionality itself; for example, the network can handle inferencing and machine computations. Of course, AI can be applied as a generic tool to optimize and facilitate efficient operations, as is the case for 5G and its evolution.

The AI for network and network for AI concepts are described below.

- **AI for network:** AI technologies, which are inherently data driven, can be integrated with the classic model-driven communication system design to cope with use cases where the model-driven design is complex or cannot achieve high enough accuracy. In AI for network, it is possible to create an intelligent communication link that adapts to a dynamic E2E transmission environment. Furthermore, by fully integrating signal processing and data analysis, we can simplify and unify the computing and inference architecture while also transforming the network from one relying on dynamic processing and response to one where proactive prediction and decision-making are possible. Although this is an area full of promise, it also poses many challenges. For example, system design is hampered by a lack of robust analytical tools and a universal neural network architecture, making it difficult to find the optimal balance among system parameters. Consequently, obtaining a solid theoretical understanding of AI is an important aspect requiring further research. In order to achieve ultimate AI support in 6G networks, it may require a more disruptive approach – one where we revisit the fundamental aspect of how the communication system transmits intelligence. A great deal more theoretical research is needed for a deeper understanding of post-Shannon communications.
- **Network for AI:** The 6G network will develop towards a more distributed architecture with embedded MEC capabilities for local data collection, training, reasoning, and inference together with global training and inference for enhanced privacy protection, lower latency, and reduced bandwidth consumption. One candidate technology that will enable such features is federated learning. During the initial design phase of 6G radio interfaces and network architecture, it is important to factor in distributed AI learning and inference in order to realize efficient large-scale intelligence. A more disruptive approach is to study the theoretical information bottleneck in the context of AI – a new direction of 6G research. This would help us compress the huge amounts of training data sent over the network using minimal resources such as bandwidth and memory.

Trend 4 – 6G native trustworthiness based on a multi-lateral trust model and new cryptographic technologies.

In 6G, mobile devices will be a portal to a cyber world that is a true replica of the physical world. As we come to depend more heavily on 6G and the services it offers, both network and service trustworthiness will be critical. As part of the network architecture design, a robust security system is the basis for establishing trusted relationships between different entities in the network. Security and network services should be jointly designed and dovetailed to meet the service requirements from both individual and business customers. The following discusses two aspects of native trustworthiness.

- **Multi-lateral trust model:** Any security architecture, regardless of whether it is centralized or decentralized, has both advantages and disadvantages. The centralized architecture employs a set of very strong security mechanisms that leverage

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strict security policies, but in terms of security dialog it involves higher complexity during roaming, handover, or re-login operations performed in the network. Consequently, the probability of being attacked is higher due to the fact that the more interfaces there are, the more vulnerable the system becomes. The decentralized architecture, which features flexible and customizable mechanisms, supports various requirements and can serve nearby services. If subjected to an attack, this architecture will contain it to within a small localized area. In cases where not all stakeholders are trustworthy, the multi-lateral trust model can be used to implement resilience so that other stakeholders remain trusted. Compared with the centralized architecture, the distributed one lacks efficient synchronization of unified security policies. A unified security architecture with multiple security attributes is therefore needed to accommodate the requirements involved in both centralized and decentralized architectures.

A multi-lateral trust model, one that is more inclusive, will serve as the foundation of future security systems. This multi-lateral trust model will help establish a resilient and native trustworthiness architecture that covers the entire 6G lifecycle. It will also flexibly implement centralized security policies, consensus-based distributed mechanisms, and verified third-party reference and verification.

- **New cryptographic algorithms:** As quantum computing continues to develop, challenges arise with regard to classical cryptography, which is based on mathematical problems such as large-prime factorization and discrete algorithms. Key generation and exchange algorithms are two indispensable elements involved in cryptography. In 6G, one-time pad (OTP) encryption can be used for full-duplex bidirectional communications at the physical layer in order to safeguard against quantum-computing-based attacks. One important aspect in terms of cryptography is that 6G requires cryptographic algorithms to complete operations within microseconds in order to ensure ultra-low latency. When quantum computing becomes a reality, quantum communication technologies are expected to be more secure due to quantum entanglement. In addition, lightweight cryptographic algorithms and privacy-compliance-related algorithms are just some of the possibilities that deserve further research in 6G.

Some of the key questions involved in implementing the preceding native trustworthiness mechanisms are as follows. (1) How will new technologies be integrated with traditional security mechanisms? (2) How will decentralized technologies be integrated with wireless network architecture? (3) How will open and transparent data security and privacy protection standards be realized? All these issues will require further study.

Trend 5 – Integrated terrestrial and non-terrestrial networks for full-earth ubiquitous access.

Today, even in developed countries, many rural and remote areas still lack high-speed Internet connections. The situation in developing countries is even worse. In fact, more than 3 billion people around the world are still without Internet access, creating a serious digital divide between the connected and the unconnected [4].

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Currently, the main barrier to achieving seamless global coverage is due to economic factors rather than technical ones. To overcome this barrier and provide seamless coverage with high-speed mobile Internet services regardless of geographical constraints, the integration of terrestrial and non-terrestrial networks is expected to be a cost-effective solution.

As the cost to manufacture and launch satellites decreases, huge fleets of small low-earth-orbit (LEO) or VLEO satellites will become a reality. Furthermore, the use of UAVs and HAPSs will mean that the coverage provided by the future mobile system will no longer be only horizontal or two-dimensional. Instead, a three-dimensional hybrid network architecture comprising multiple layers and numerous moving access points will enable communication and navigation services anywhere and at any time. This means a radical shift in terms of cell planning, cell acquisition and handover, and wireless backhaul.

At present, UAVs and HAPSs are designed and operated separately, but in the future 6G networks their functions and operations along with their resource and mobility management are expected to be tightly integrated. Such an integrated system will identify each user device with a unique ID, unify billing processes, and continuously provide high-quality services via optimal access points.

In order to seamlessly integrate a new UAV or LEO satellite without the need for manual configuration, the integrated network requires self-organization. With intelligent air interface design, the addition and deletion of an access point would be transparent to user devices, with respect to the physical-layer procedures (such as beamforming, measurement, and feedback) associated with the access point. Given that the deployment, maintenance, and energy source of satellites differ completely from those of terrestrial networks, it is expected that new operating and business models will emerge.

Trend 6 – Green and sustainable networking for low total cost of ownership (TCO) and sustainable development worldwide.

The increasing number of connected devices, base stations, and network nodes will not only lead to a massive surge of data traffic, but also result in a substantial increase in energy consumption across all parts of the network. Energy efficiency, defined as bits/joule, has long been a focal design target. In the 6G network design, it will become an even more important requirement – it will no longer be just a nice-to-have feature; rather, it will be a make-or-break requirement for 6G mobile networks.

As of today, ICT produces about 2% of the global greenhouse gas emissions (of which, mobile networks represent about 0.2%) [12]. This percentage is expected to increase year-over-year. For 6G, in addition to energy efficiency, it will be important to reduce the energy consumption of networks. This is necessary to not only cut the electricity bill but also reduce greenhouse gas emissions, an important social commitment. At the same time, however, it will also be necessary to consider both capital expenditure (CAPEX) and operational expenditure (OPEX). While the design of cost-effective and energy-efficient networks moves the ICT industry closer to sustainable development, the ICT industry as a whole can play an important role in reducing global CO_2 emissions for a cleaner and healthier living environment. It is expected that ICT can achieve a 20% reduction of global CO_2 emissions by 2030 compared with 2015 levels [13]. Meanwhile, the 6G communication system should support new business use cases and application scenarios to facilitate other industries while also enabling sustainable social development.

The so-called green radio network is a vast research discipline. The potential energy-efficiency technologies span architectures, materials, hardware components, algorithms, software, and protocols. Dense network deployment (leading to shorter propagation distance), centralized RAN architecture (resulting in fewer cell sites and higher resource efficiency), energy-aware protocol design, and cooperation between users and base stations are some factors that need to be carefully considered in order to achieve an energy-efficient 6G communication system. Another challenge is the need for innovative ways to deal with the reduced power amplifier (PA) efficiency as we move towards using higher and higher frequencies. In addition, renewable energy and radio frequency (RF) energy harvesting technologies should also be considered.

On the other hand, as AI capabilities become pervasive across data centers, edge nodes, and even mobile devices, the energy consumption involved in AI learning and training becomes a key issue that must be addressed. It was pointed out in [14] that training a single AI model emits as much carbon as five cars produce throughout their lifetime. Data centers alone consumed more than 2% of the world's electricity in 2018, and this percentage is expected to increase as more AI-enabled edge nodes and devices will emerge by 2030. Some recent research shows that training a once-for-all network that supports diverse architectural settings would significantly reduce CO_2 emissions compared with finding a specialized neural network and training it from scratch for each case by using neural architecture search [15].

1.3.2 Typical Use Cases

As new technologies are increasingly adopted in wireless communications systems, many aspects of our daily lives will be augmented by ultra-high-speed wireless connections, AI, and advanced sensor technologies. Simply put, the way we communicate and interact with technology will change as we know it.

In addition to broadband services, 5G has taken a leap towards low-latency and highly reliable wireless access, thereby enabling a set of vertical and IoT applications. ITU-R identified three types of usage scenarios for 5G applications (eMBB, URLLC, and mMTC) in the IMT-2020 vision document [16]. As intelligence and sensing capabilities are introduced in 6G, and coverage is extended beyond terrestrial, the next-generation networks will create new applications and improve existing applications. Some of these applications may have already been discussed in the 5G vision, even though they may not have been included in 5G deployments due to technological limitations or to an immature market. We'll focus on the use cases that the 5G network cannot support (such as sensing), as well as the use cases that were discussed but not extensively adopted in 5G such as intelligence and enhancements to the three 5G applications (eMBB+, URLLC+, and mMTC+). We identify six categories for the potential use cases of 6G, as shown in Figure 1.6.

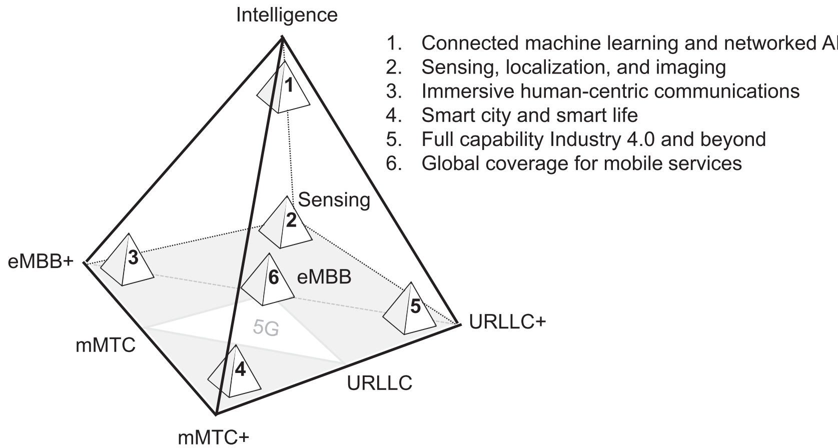

Figure 1.6 Overview of 6G use cases.

- **Immersive human-centric communications:** The pursuit of a better communication experience never stops. In order to provide immersive experience in remote presence and human-centric applications such as AR, VR, and MR as well as holographic communications, we need to continuously push the display resolution towards the human perception limit. As such, an ultra-high data rate of up to Tbit/s is required, and today's 5G network is incapable of achieving this. To avoid motion sickness (dizziness and fatigue) and obtain real-time haptic feedback from teleoperation, extremely low E2E network latency is another key requirement approaching the limits of human senses and perception.
- **Sensing, localization, and imaging:** In addition to communication, the use of higher-frequency bands (THz and mmWave) delivers other capabilities such as sensing, imaging, and localization. As a result, various value-added innovative applications are introduced, such as high-precision navigation, gesture recognition, mapping, and image reconstruction. Compared with communication, sensing, localization, and imaging have different requirements, such as sensing resolution and accuracy for range, angle, or velocity. They also include a new set of performance metrics, such as the probabilities of misdetection and false alarm.
- **Full-capability Industry 4.0 and beyond:** The industry use cases of 5G have been extensively studied [1]. Although 5G has been designed with low latency and high reliability, some of these cases pose extremely high requirements (such as precise motion control) that exceed 5G's capabilities. That said, 6G will enable these use cases through technologies that support ultra-high reliability, extreme low latency, and the deterministic communication capability. Moreover, as new AI-based human–machine interaction methods become viable, future automated manufacturing systems will be centered on collaborative robots, cobots, or even cyborgs. Real-time intelligence interaction between robots and humans requires even lower latency and higher reliability in comparison with 5G.

- **Smart city and life:** A massive number of sensors will be deployed for smart transportation, building, health, car, city, and factory. These sensors will collect a huge amount of data for AI algorithms, which are then used to provide AI as a service. It is also believed that we will live in a world where physical reality is accompanied by a digital twin in the cyber world. Phrased differently, automation and intelligence will be created within the cyber world and delivered to the physical world through 6G wireless networks. To achieve this, it is imperative that we develop extensive sensing capabilities for retrieving the big data used to train deep neural networks (DNNs). This, in turn, demands a very-high-throughput wireless link for collecting sensing data in real time. As such, a massive number of reliable and secure connections are required for the 6G-enabled smart urban city and life use cases.
- **Global coverage for mobile services:** In order to provide seamless mobile services everywhere on earth, 6G aims for integrated terrestrial and non-terrestrial communications. In such an integrated system, a mobile user with a single device can access mobile broadband services in both urban and rural areas, or even on moving planes and ships. In these scenarios, the best links for terrestrial and non-terrestrial networks are dynamically optimized without interrupting ongoing services. Self-driving enthusiasts will also benefit from the integrated system with seamless high-precision navigation in all types of geographical areas. Some of the other potential use cases involve a wide range of IoT connections for real-time environmental protection and precise agriculture.
- **Connected machine learning and networked AI:** Full-scenario use of AI capabilities is a fundamental use case for 6G. Basically, on the one hand, AI capabilities can be augmented and integrated into most of the functions, features, and capabilities of 6G. On the other hand, almost all 6G applications will be AI-based, and AI can also be applied to all the preceding use cases to achieve different levels of automation. Put differently, there are challenges and limitations involved with providing AI as an OTT service. The first challenge is the fact that machine learning requires the transfer of huge amounts of data to data centers, especially for customized AI services. The second challenge is directly related to the local data governance requirement. More specifically, the transfer of data to overseas data centers is not permitted. The third challenge involves the interaction of different AI agents (even if separated remotely) through the 6G network. As one of the most important use cases, distributed machine learning agents will be fully connected through the 6G network to achieve networked intelligence while also allowing for better data privacy protection. In light of this, connected machine learning and networked AI will essentially involve the following aspects: the 6G design for maximizing the machine learning capability; network architecture that supports distributed and AI-at-network-edge capabilities for real-time AI services; high-capacity, low-latency, and highly reliable AI inference and action. Furthermore, AI will serve as a native feature of 6G, thereby facilitating the design of future transmission schemes, intelligent control and resource management, as well as "zero-touch" network operations.

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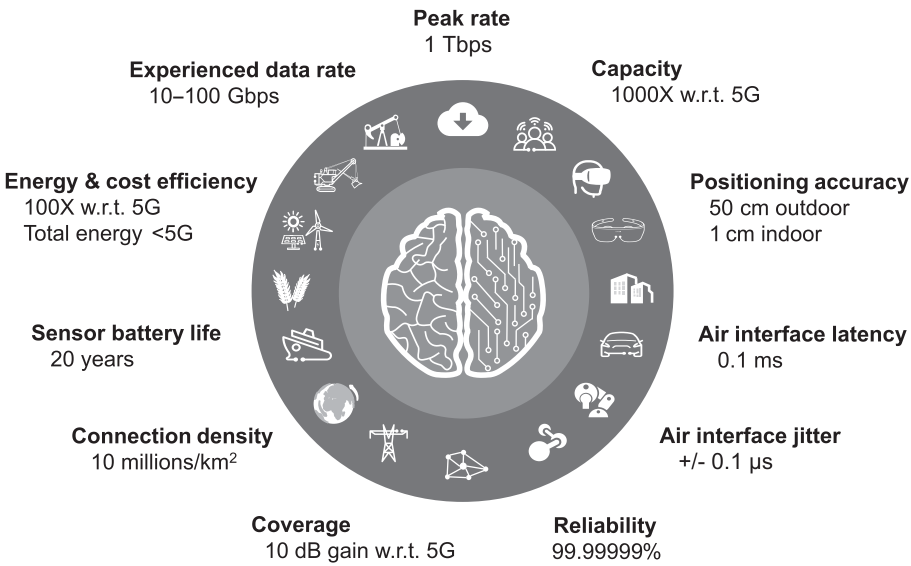

Figure 1.7 Summary of KPIs for radio access networks.

1.3.3 Target KPIs

In order to achieve ultimate user experience in all use cases, 6G must realize significant improvements in terms of key capabilities. Based on the upgrade trends of earlier mobile generations, the improvements in 6G are expected to increase by 10 to 100 times compared with 5G. Our preliminary expectations are shown in Figure 1.7 and elaborated as follows.

Very high data rate and spectrum efficiency.

To realize human-centric communication with immersive experience will pose very high demand on the bandwidth. The transmission of 300 degree AR/VR and holographic information may require a data rate from several Gbit/s to a few Tbit/s, depending on factors such as the resolution, size, and refresh rate of images.

In IMT-2020 (5G), the ITU-R minimum requirements for the peak and user-experienced data rates are 10–20 Gbit/s and 100 Mbit/s, respectively [17]. In 6G, the peak and user-experienced data rates should be 1 Tbit/s and 10–100 Gbit/s, respectively. In addition, 6G is expected to further utilize spectrum, improving the peak spectrum efficiency by 5 to 10 times compared with 5G.

Very high capacity and ultra-massive connectivity.

The area traffic capacity is the total traffic throughput per geographic area. It is the product of the area's connection density (the total number of devices per unit area) and the average data rate provided for users. In 5G, the ITU-R minimum requirement for connection density is 1,000,000 devices per km^2 [17]. In 6G, where we must support use cases such as Industry 4.0 with connected intelligence and smart city in the next 10 years and beyond, the connection density should be increased by about 10 to 100

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times, resulting in up to 100 million/km^2. Such a massive number of connections should be able to accommodate diversified types of services with different characteristics, (e.g., different throughput, latency, and QoS). In this regard, the 6G system capacity should be 1000 times larger than 5G in order to provide high-quality services for a large number of connections.

Very low latency and jitter, and ultra-high reliability.

In some IoT use cases such as autonomous driving and industry automation, it is critical that data are delivered in time (with low latency and jitter). 6G air interfaces will achieve a latency of 0.1 ms and a jitter of +/−0.1 s. Taking into account the requirements of remote XR presenting services, the total E2E round-trip latency should be 1–10 ms. In addition to low latency, IoT applications also require reliability (i.e., the correct transmission of information). ITU-R requires that reliability in 5G be 99.999% for URLLC services. In 6G, where various vertical applications are expected to be more prevalent, a ten-fold increase in reliability is needed, reaching 99.99999%.

Very high localization, sensing accuracy, and resolution.

Sensing, localization, and imaging are new functions in 6G, marking a significant step forward for connected intelligence, as will be discussed in Chapter 9. With the increased resolution of the frequency range – up to THz – and advanced sensing technologies, 6G is expected to provide an ultra-high localization accuracy of 50 cm for outdoor scenarios and 1 cm accuracy for indoor scenarios. For other sensing services, as will be described in Chapter 5, the extreme sensing accuracy and resolution can be 1 mm and 1 cm, respectively.

Very wide coverage and very high mobility.

To provide high-quality mobile Internet services with wider coverage, the link budget for 6G air interfaces should be increased by at least 10 dB compared with 5G. This applies to MBB services with a guaranteed data rate in addition to NB-IoT services. The 6G coverage should not be defined only by link budget. By integrating both terrestrial and non-terrestrial networks, 6G should achieve 100% coverage of the earth's surface and population, connecting unconnected areas and people.

In addition, 6G will support coverage for aircrafts traveling at speeds around 1000 km/hr, much higher than 5G (500 km/hr, mainly for high-speed trains).

Very high energy and cost efficiency.

Energy consumption is a challenging aspect in 6G systems. On the one hand, this is due to transmission at very high frequency bands, very large bandwidth, and very large numbers of antennas. The lower PA efficiency and increased number of RF chains are the two key aspects to address. On the other hand, with the convergence of communication and computing, and the support of native AI, AI training and inference in 6G networks will consume more energy. This means that the energy consumption per bit in 6G should be at least 100 times lower than that in 5G in order to achieve comparable levels of total energy consumption. From the perspective of devices, with increased data rates, the energy efficiency for signal processing should be increased accordingly. Furthermore, sensing devices should support a battery life of up to 20 years for use in smart city, smart building, smart home, and smart health scenarios.

Native AI.

As discussed in Section 1.3.1, the native AI support in 6G mobile communications systems includes two aspects: AI for network and network for AI.

- **AI for network** enables an intelligent framework for designing air interfaces and network functions, supporting E2E dynamic transmission, truly zero-touch network operation, and automatic creation of specialized network slices for diverse services and diverse enterprises.
- **Network for AI** demands a more distributed architecture with embedded mobile edge computing capabilities to combine local data collection, training, and reasoning/inference with global training and inference for better privacy protection and lower latency/bandwidth consumption.

Native trustworthiness.

6G will strengthen the connection between the physical and digital worlds, becoming an integral part of our life. Trustworthiness is a fundamental aspect for any network service and covers topics including security, privacy, resilience, safety, and reliability [18].

- **Security** is a condition that results from the establishment and maintenance of protective measures that enable an organization to perform its mission or critical functions despite risks posed by threats to its use of systems, as defined in [19]. Protective measures may involve a combination of deterrence, avoidance, prevention, detection, recovery, and correction that should form part of the organization's risk management approach.
- **Privacy** is freedom from intrusion into the private life or affairs of an individual when that intrusion results from undue or illegal gathering and use of data about that individual, as defined in [20].
- **Resilience** is the ability to quickly adapt and recover from any known or unknown changes to the environment through holistic implementation of risk management, contingency, and continuity planning, as defined in [21].
- **Safety** is the freedom from conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment, as defined in [22].
- **Reliability** is the ability of a system or component to function under stated conditions for a specified period of time, as defined in [23].

1.4 Structure of the Book

This book is composed of seven parts that cover specific topics about 6G. Part I (Chapter 1) describes the evolution of mobile communications from 2G to 6G and

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the overall vision of 6G, identifying six technology trends that are central to the three fundamental drivers for the future of connected intelligence.

In Part II, we discuss potential use cases for 6G and analyze the key performance requirements. The use cases range from evolutionary 5G ones that will gain popularity and mature in 6G due to its larger capacity, lower latency, and higher reliability, to brand new ones made possible by the new functions and capabilities that 6G offers. Part II organizes the typical use cases into six categories, describing each one in separate chapters. They cover human-centric communications with extremely immersive experience (Chapter 2); highly accurate sensing, localization, and imaging plus enhanced human sensing (Chapter 3); full-capability Industry 4.0 with connected intelligence (Chapter 4); smart city and smart life (Chapter 5); global 3D coverage for mobile services with integrated terrestrial and non-terrestrial communications (Chapter 6); and native AI support in all use cases (Chapter 7).

Part III explores the scope and boundaries of 6G design, discussing the theoretical foundations for 6G radio technologies and network technologies before examining a range of enabling technologies with the potential to achieve key performance indicators (KPIs).The introduced content covers theoretical foundations for native AI and machine learning (Chapter 8), theoretical foundations for massive capacity and connectivity (Chapter 9), theoretical foundations for future machine type communications (Chapter 10), as well as theoretical foundations for energy-efficient systems (Chapter 11).

In Part IV, we analyze the future International Mobile Telecommunications (IMT) spectrum from the perspective of communication and sensing (Chapter 12), and the corresponding channel modeling methodologies and some example channel measurements (Chapter 13). Then, to provide a broad and comprehensive understanding of how 6G will mature over the next 10 years, we describe potential new materials for hardware production (Chapter 14), new antenna structures for ultra-massive multiple-input multiple-output (MIMO) systems (Chapter 15), new radio frequency components to support the use of the THz band (Chapter 16), computing evolution following the end of Moore’s law (Chapter 17), and new demands and features for terminal devices (Chapter 18).

Part V focuses on the overall design principles and potential enabling technologies for 6G air interfaces. We describe the paradigm shifts in designing air interfaces compared with 5G and earlier generations in the introduction to the Part, and then discuss a range of enabling technologies. These potential technologies are intelligent air interface (Chapter 19), integrated non-terrestrial and terrestrial communication (Chapter 20), integrated sensing and communication (Chapter 21), new waveform and modulation (Chapter 22), new coding (Chapter 23), new multiple access (Chapter 24), ultra-massive MIMO (Chapter 25), and super short-range communication (Chapter 26). For each technology, we describe the background and motivation for its use, examine the existing solutions, clarify the new design expectations, and highlight the potential research problems and directions for future study.

Similarly, Part VI focuses on the design principles and potential enabling technologies for 6G network architecture design. It also starts with the paradigm shifts in

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designing the network architecture in the introduction to the part. Following that, it delves into several of the new major features and technologies involved in 6G network architectures. They are architecture technologies for network AI (Chapter 27), user-centric network (Chapter 28), native trustworthiness (Chapter 29), data governance (Chapter 30), multi-player ecosystems (Chapter 31), and integrated non-terrestrial networking (Chapter 32).

Part VII (Chapter 33) concludes the book by describing the current status of the 6G ecosystem globally, covering research projects, platforms, workshops, and papers on 6G, and then predicts the potential roadmap towards 2030.

References

[1] 5G-ACIA. [Online]. Available: https://www.5g-acia.org/

[2] 5GAA. [Online]. Available: https://5gaa.org/

[3] ITU-R, "IMT traffic estimates for the years 2020 to 2030," Report ITU-R M.2370-0, July 2015.

[4] "The mobile economy 2020," Intelligence, GSMA, 2020.

[5] "Touching an intelligent world," Sept. 2019. [Online]. Available: https://www.huawei.com/minisite/giv/Files/whitepaper_en_2019.pdf

[6] "Terahertz spectroscopic system TAS7400 product specification." [Online]. Available: https://www.advantest.com/documents/11348/146157/spec_TAS7400_EN.pdf

[7] "2019 ICT Sustainable development goals benchmark," 2019. [Online]. Available: https://www.huawei.com/minisite/giv/Files/whitepaper_en_2019.pdf

[8] United Nations Development Programme, "Goal 11: Sustainable cities and communities." [Online]. Available: https://www.undp.org/content/undp/en/home/sustainable-development-goals/goal-11-sustainable-cities-and-communities.html

[9] "ICTs for a sustainable world #ICT4SDG," ITU, 2019. [Online]. Available: https://www.itu.int/en/sustainable-world/Pages/default.aspx

[10] V. Bush, *Science, the endless frontier*. Ayer Company Publishers, 1995.

[11] N. C. Thompson, K. Greenewald, K. Lee, and G. F. Manso, "The computational limits of deep learning," *arXiv preprint arXiv:2007.05558*, 2020.

[12] "ICT sector helping to tackle climate change," Dec. 2016. [Online]. Available: https://unfccc.int/news/ict-sector-helping-to-tackle-climate-change

[13] "SMARTer2030: ICT solutions for 21st century challenges," The Global eSustainability Initiative (GeSI), Brussels, Brussels-Capital Region, Belgium, Technical Report, 2015.

[14] E. Strubell, A. Ganesh, and A. McCallum, "Energy and policy considerations for deep learning in NLP," *arXiv preprint arXiv:1906.02243*, 2019.

[15] H. Cai, C. Gan, T. Wang, Z. Zhang, and S. Han, "Once-for-all: Train one network and specialize it for efficient deployment," *arXiv preprint arXiv:1908.09791*, 2019.

[16] ITU-R, "IMT Vision – framework and overall objectives of the future development of IMT for 2020 and beyond," Recommendation ITU-R M.2083-0, Sept. 2015.

[17] ITU-R, "Minimum requirements related to technical performance for IMT-2020 radio interface(s)," Report ITU-R M.2410-07, Nov. 2017.

[18] E. R. Griffor, C. Greer, D. A. Wollman, and M. J. Burns, "Framework for cyber-physical systems: Volume 1, overview, Version 1.0," NIST Special Publication, 2017.

[19] C. Dukes, "Committee on national security systems (CNSS) glossary," CNSSI, Fort Meade, MD, USA, Technical Report, vol. 4009, 2015.
[20] S. L. Garfinkel, "De-identification of personal information," National Institute of Standards and Technology (US Department of Commerce), 2015.
[21] M. Swanson, *Contingency planning guide for federal information systems*. DIANE Publishing, vol. 800, 2011.
[22] "System safety," Department of Defense Standard Practice, May 11, 2012. [Online]. Available: https://e-hazard.com/wp-content/uploads/2020/08/department-of-defense-standard-practice-system-safety.pdf
[23] IEEE Standards Coordinating Committee, "IEEE standard glossary of software engineering terminology (IEEE Std 610.12-1990). Los Alamitos, CA," CA: IEEE Computer Society, vol. 169, 1990.