Chapter 3
6G Enabling Technologies

Michele Polese, Marco Giordani, Marco Mezzavilla, Sundeep Rangan, and Michele Zorzi

Abstract While network operators have already started deploying commercial 5th generation (5G) networks, existing cellular technologies may lack the level of reliability, availability, and responsiveness requested by future wireless applications. For this reason, the research community at large is already defining the most promising technologies that can enable 6th generation (6G) wireless systems. We have identified three critical innovations: (1) communications at Terahertz and optical frequencies for ultra-high-speed broadband access, (2) cell-less architectures to enable ubiquitous 3D coverage, and (3) intelligent networks to simplify the management of complex networks and reduce costs. In this chapter, after summarizing envisioned use cases and corresponding Key Performance Indicators (KPIs) in the 6G ecosystem, we will review the characteristics of these innovations and speculate about whether and how they will satisfy the most stringent 6G network demands in a holistic fashion, in view of the foreseen economic, social, technological, and environmental context of the 2030 era.

1 Introduction

The advent of a multitude of new data-hungry, delay-sensitive mobile services will likely introduce severe challenges to current 5G systems. Figure 3.1 illustrates how the evolution of mobile applications has introduced over the years an exponential increase of mobile data consumption. In the next decade, the radical automation

M. Polese
Institute for the Wireless Internet of Things, Northeastern University, Boston, MA, USA
e-mail: m.polese@northeastern.edu

M. Giordani · M. Zorzi
Department of Information Engineering, University of Padova, Padova, Italy
e-mail: giordani@dei.unipd.it; zorzi@dei.unipd.it

M. Mezzavilla (✉) · S. Rangan
NYU Tandon School of Engineering, Brooklyn, NY, USA
e-mail: mezzavilla@nyu.edu; srangan@nyu.edu

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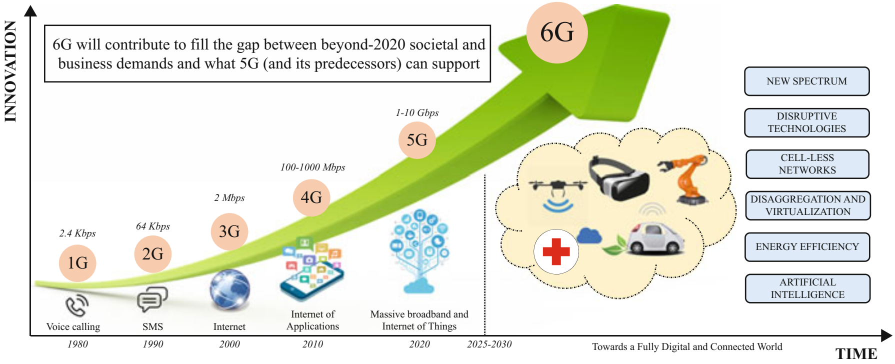

Fig. 3.1 Cellular networks generations (from 1G to 6G) and representative applications. Adapted from [1]

of industrial manufacturing, with concepts such as digital twin and Industry 4.0, the widespread proliferation of unmanned systems, both terrestrial and aerial, along with the millions of sensors that will be embedded into our cities, will call for a fundamental redesign of current cellular networks.

Mobile networks will provide a fundamental support to such smart environments, constituting their nervous system, as we discuss in [1]. Wireless links will transfer much greater amounts of data, at gigabit-per-second rates. Moreover, 6G connection will continue the trend toward a ubiquitous connectivity, not only for human communications, but, following the Internet of Things (IoT) paradigm, also to network together autonomous vehicles, sensors, wearable and medical devices, distributed computing resources and robots [2].

5G networks have already enabled impressive performance advancements toward a fully connected wireless fabric, by (1) expanding mobile cellular networks into new frequency bands (e.g., with millimeter wave (mmWave) communications), (2) introducing advanced spectrum usage and management, and (3) completely redesigning the core of the cellular network. However, the expected requirements of 6G applications will exceed the capabilities of the current 5G specifications. Wireless networks will need to support data rates in the order of terabits per second, latency values below the millisecond, and ten million connected devices per km^2.

This has recently sparked the interest of the research community toward the definition of the requirements and the technologies of a new generation of mobile networks, i.e., 6G systems, that will meet the connectivity demands of future intelligent and autonomous digital ecosystems. Following our discussion in [1], this chapter aims at illustrating what is the set of technologies that we envision as a likely candidate for more advanced and vertical-specific wireless networking solutions with respect to the state of the art of communication and networking technologies. In particular, we first analyze several potential use cases for future connected systems, and then map them to their key requirements in terms of latency, throughput, coverage, reliability, and other factors. Along these lines, this book chapter describes some scenarios in which the 5G networks being deployed today would be able to satisfy such performance demands.

Based on this analysis, the second part of the chapter highlights possible technological enablers for 6G, which include radically new communication technologies, network architectures, and deployment models to satisfy the relevant KPIs in each connected scenario. In particular, we foresee the development of:

- *New technologies at the physical layer, and the exploitation of frequencies above 100 GHz:* the vastly available spectrum in the Terahertz and optical bands will unlock unprecedented wireless capacity [3–5]. However, to unleash the true potential of these portions of the wireless spectrum, new disruptive communication technologies need to be introduced.
- *Multi-dimensional network architectures:* more complex networks will emerge as a result of the more advanced 6G use cases. To this end, we expect that 6G networks will provide a 3D coverage [6, 7], i.e., to support aerial platforms, the aggregation of heterogeneous technologies for access and backhaul, and the fully virtualized radio access and core network elements [8].
- *Prediction-based network optimization:* the multi-dimensional architecture described in the previous point will dramatically increase the complexity of the networks. To address this issue, 6G will have to increasingly rely on automated and intelligent techniques, deployed at each layer and node of such multi-dimensional networks [9]. In particular, distributed and unsupervised learning, and knowledge sharing will constitute key enablers for real-time decisions, that will be critical to maintaining and operating these complex networks.

Prior work has discussed possible technological advancements for 6G networks (e.g., [10, 11]). With respect to these contributions, in this book chapter and in [1] we outline a system-level vision, which starts by identifying the future use cases under development today for 6G systems and their performance requirements, and then highlights the challenges and opportunities associated to 6G technological enablers from a full-stack, end-to-end perspective. Most importantly, we select with a critical approach a subset of the various solutions that have been identified in the wireless research literature as the most promising candidates for an actual deployment ten to 15 years from today. Some of these technologies are incremental with respect to 5G, while other will represent a major breakthrough. The combination of these two approaches will clearly define a new generation of mobile networks, with solutions that have not been thoroughly addressed or cannot be properly included in current 5G standards developments.

We expect that this book chapter will help promote research efforts toward the identification of new communication and networking paradigms to meet the boldest requirements of 6G scenarios.

2 6G Use Cases

5G technologies are associated with trade-offs on power consumption, latency, cost of deployment and operations, hardware complexity, end-to-end reliability, throughput, and communication resilience. 6G innovations, on the contrary, will be developed in such a way that stringent network demands (in terms of ultra-high reliability, capacity, energy efficiency, and low latency) are jointly met in a holistic fashion.

In this section, we review the proprieties, characteristics and foreseen requirements of applications that, for their complementarity and generality, can be considered as good representatives of next-generation 6G services. Although some of these applications have already been discussed in 5G, we believe that they will likely not be part of future 5G deployments either due to technological limitations or because the market will not be mature enough to support them (especially within the very short timeframe in which 5G is supposed to be released). Figure 3.2 illustrates the KPIs of the use cases we will describe later in this section.

Augmented Reality (AR) and Virtual Reality (VR)
Current mobile networks have paved the way toward wireless video streaming, which represents one of the applications that contribute to the largest portion of mobile data traffic. The increasing use of such streaming and multimedia services has justified the introduction of new frequency bands (i.e., mmWaves) in 5G networks, to increase the capacity of the network. Nonetheless, following the multi-Gbps opportunity introduced by 5G mmWave communications, the multimedia ecosystem is developing new technologies and applications (i.e., augmented reality (AR) and virtual reality (VR)) which are more data-hungry, and extend the two-dimensional video screen to 3D application. Then, just like wireless video streaming

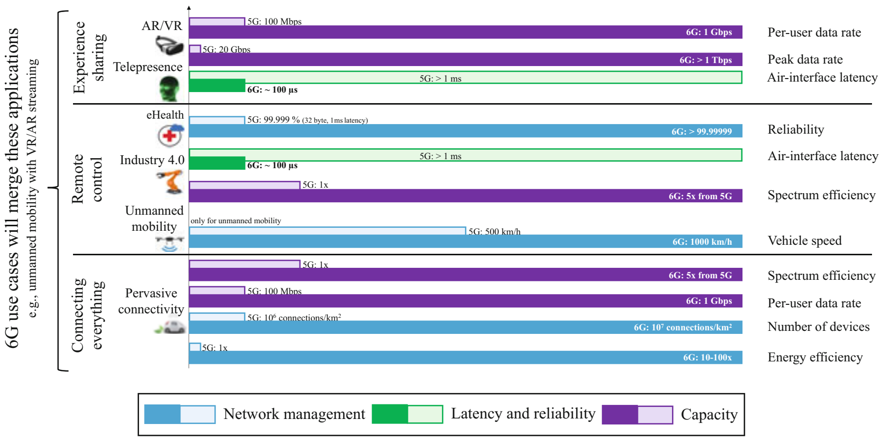

Fig. 3.2 KPIs of future 6G use cases, together with the improvements with respect to 5G networks, using data from [2, 10–17]. Adapted from [1]

has saturated 4G deployments, the spreading of AR and VR will exhaust the bandwidth available in the 5G spectrum, and will eventually call for wireless system capacity above 1 Tbps, which exceeds the 20 Gbps peak throughput objective outlined for 5G [2]. Furthermore, real-time interaction among different users of the same AR or VR setup introduces tight constraints on the latency that the network needs to provide. Therefore, it is not possible to heavily encode and compress AR/VR content, as coding and decoding may take too long. Consequently, the data rate to be allocated to each user needs to be in the order of Gpbs, while 5G only foresees a 100 Mbps target.

Holographic Telepresence (Teleportation)
Humans have always pursued the dream of teleportation as a means to deliver life-sized three-dimensional digital representation of all human senses in real time. Among several other benefits, this technology can allow virtual interaction of people during business events and meetings, and remove geographical time and distance barriers. This innovation, however, raises several challenges in 6G networks from a communication point of view. Some literature works, e.g., [12], make the case that the throughput requirements for the transmission of a 3D raw hologram, without compression, would be in the order of several Tbps, depending on the sensor's resolution and frame rate. The latency requirement will then go below the ms threshold to make the holographic experience smoother and more immersive. Furthermore, teleportation will require the processing of a very large number of streams generated from sensors at different view angles, as opposed to the few required for VR/AR, thereby raising stringent synchronization requirements.

eHealth
6G will revolutionize the health-care sector promoting workflow optimization, remote/virtual patient monitoring, and robotic telesurgery, while guaranteeing more efficient and affordable patient assistance. In particular, 6G will accomplish a transition towards a "care outside hospital" paradigm, where health-care services can be offered directly in the homes of the patients, thus reducing management and administrative costs for health facilities as well as making health-care assistance more accessible to the most unprivileged countries in the world. Besides the high cost, the current major issue for the development of eHealth services is the lack of real-time tactile feedback [13]. Furthermore, the proliferation of telemedicine applications will require the maintenance of continuous connectivity with very high reliability (>99.99999%, due to the potentially fatal consequences of communication failures), ultra-low latency (sub-ms), and support for mobility. These ambitious KPIs will be satisfied with increased spectrum availability, together with the evolution of current artificial intelligence paradigms, as expected in 6G networks [2].

Pervasive Connectivity
Although 5G networks support more than 1,000,000 connections per km^2, mobile traffic will grow threefold from 2016 to 2021, thereby pushing the number of connected nodes to the extreme, with at least an order of magnitude increase in

the number of devices per km^2 [2]. 6G networks will indeed connect smartphones, personal devices and wearables, IoT sensors in smart city deployments, robots, Unmanned Aerial Vehicles (UAVs), vehicles, and so on. This will further increase the load on already stressed deployments, which will not be capable of supporting the connectivity requests of each and every user with the performance requirements illustrated in Fig. 3.2. Moreover, while 80% of the wireless data traffic is consumed by indoor users, cellular networks never really targeted indoor coverage. For example, 5G infrastructures, which may be operating in the mmWave spectrum, will hardly provide indoor connectivity as high-frequency radio signals cannot easily penetrate solid material. Furthermore, 5G densification presents scalability issues and high deployment and management costs for operators. 6G networks will instead provide seamless and pervasive connectivity in different scenarios, satisfying demanding Quality of Service (QoS) requirements in both outdoor and indoor scenarios with a resilient and low-cost infrastructure. Additionally, 6G deployments will need to be more energy efficient with respect to 5G (with a 10–100x improvement in efficiency), otherwise the overall energy consumption would prevent scalable deployments with low environmental impact.

Industry 4.0 and Robotics

6G will foster and further develop the manufacturing revolution known as Industry 4.0, already started with the support of 5G networks. Industry 4.0 foresees a digital conversion of the manufacturing process toward a full deployment of cyber physical systems on the production lines, enabling connected services such as predictive diagnostics, maintenance, and flexible, cost-effective and efficient machine-to-machine interactions [14]. Moreover, digital twins will support remote inspection and development of industrial products, through a highly reliable, high fidelity digital representation of the real systems. Fully automated processes, however, introduce an additional set of requirements in terms of reliable and isochronous data transfer [15], which 6G needs to address through the disruptive set of technologies we will describe later in this book chapter. For example, the control of industrial actuators needs real-time communications with a delay jitter that should be in the order of 10^{-6} s, while digital twin and AR/VR industrial use cases require Gbps peak data rates.

Unmanned Mobility

The transition towards smart and connected transportation offers safer traveling, improved traffic management, automated driving, and support for infotainment for drivers and passengers, with an estimated market of more than 7 trillion USD [16]. Connected vehicles require high volumes of data to be exchanged among cars and clouds for high-resolution dynamic mapping, sensor sharing, and computational offloading: the data rate requirements will reach the Terabytes per driving hour [17], far beyond current network capabilities. Furthermore, automated driving requires unprecedented levels of reliability and low latency (>99.99999% and <1 ms, respectively), especially in high mobility scenarios (up to 1000 km/h). Another very important requirement will be ensuring accurate positioning for moving objects (up to 10 cm, depending on the target use case) [18]. Besides cars, flying vehicles (e.g., drones) also have a great potential for 6G. In this perspective, advances in hardware, software, and spectrum solutions will pave the way towards more efficient and flexible deployment and management of groups of vehicles of a different nature, as we will discuss in Sect. 3.

This wide diversity of use cases is a unique characteristic of the 6G paradigm, whose potential will be fully unleashed only through breakthrough technological advancements and novel network designs, as described in the next section.

3 6G Enabling Technologies

In the following paragraphs, we will review the technologies we identified as enablers of the applications introduced in Sect. 2, following also the discussion in [1]. Notably, we focus on the technologies that were deliberately left out from current 5G standards specifications (i.e., from 3GPP NR Releases 15 and 16), and on solutions that are part of today's research but not yet ready for a commercial deployment. We will consider wireless technologies that exploit new portions of the spectrum in Sect. 3.1, new multi-dimensional architectural breakthroughs in Sect. 3.2, and finally disruptive applications of machine learning and artificial intelligence for predictive network optimization in Sect. 3.3. Table 3.1 summarizes the main technological innovations that could be introduced in 6G networks, considering their potential, the associated challenges, and the use cases introduced in Sect. 2 they empower.

3.1 Novel Wireless Paradigms and Frequencies Above 100 GHz

It is possible to characterize a new generation of wireless networks by identifying a set of new communication techniques that extend the capabilities of mobile devices beyond what was possible before, for example, in terms of latency and data rates. To this end, connected services in 5G networks are enabled by massive Multiple Input, Multiple Output (MIMO) and the mmWave spectrum. Along this line, to meet the KPIs described in Sect. 2, 6G deployments will combine traditional frequency bands (i.e., mmWaves and sub-6 GHz) and portions of the spectrum that have not been included in any cellular standard so far, i.e., Visible Light Communications (VLC) and the Terahertz band. Figure 3.3 depicts the path loss associated with each of these bands, for deployment scenarios that are representative of each technology, to illustrate how the different portions of the wireless spectrum provide distinct challenges and opportunities. In the following paragraphs, we will focus on the two novel spectrum bands that will be most likely considered for use in 6G.

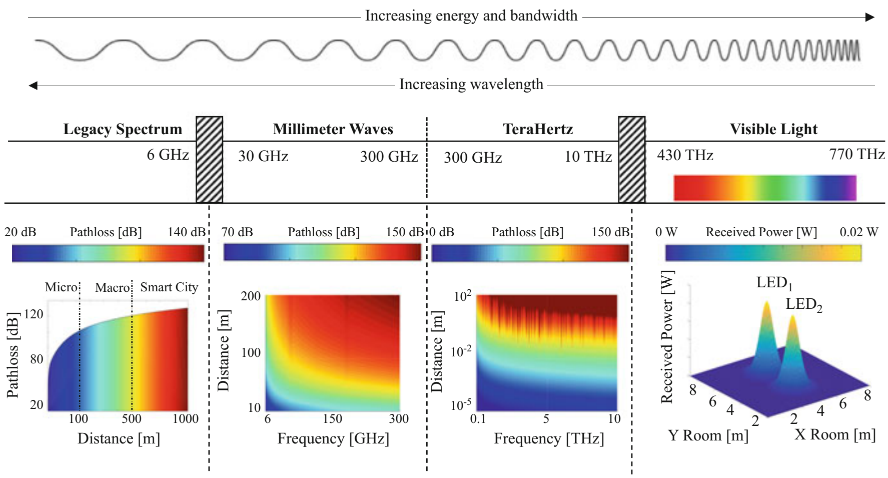

Fig. 3.3 Pathloss for sub-6 GHz, mmWave and Terahertz bands, and received power for VLC. The sub-6 GHz and mmWave pathloss follows the 3GPP models considering both LOS and NLOS conditions, while LOS-only is considered for Terahertz [19] and VLC [20]. This figure is taken from [1]

- **Terahertz communications** operate between 100 GHz and 10 THz [19] and, compared to mmWaves, bring to the extreme the potential of high-frequency connectivity, enabling data rates in the order of hundreds of Gbps, in line with the boldest 6G requirements. The THz bands would be combined with highly directional antenna arrays for massive spatial multiplexing. Also, due to the small wavelength, even high-rank line-of-sight MIMO links [21] may be possible at moderate distances to support multiple spatial paths in the absence of scattering. The small wavelengths may also enable new kinds of ultra-small-scale electronic packaging solutions for the RF and antenna circuitry, particularly in short-range applications. There are, however, significant challenges: THz RF devices are still in the early stages of development and currently significantly less power efficient (see, e.g. [22]). Due to the wide bandwidths and large number of elements to support, the digital baseband processing power can also be significant [23, 24]. Also, similar to the mmWave bands, THz signals are extremely susceptible to blockage. For very long links (e.g. >1 km), molecular absorption can also be problematic, particularly in heavy rain and fog (See [19] and Fig. 3.3). Nevertheless, some early experiments have demonstrated the potential for medium-range (e.g. 100 m) NLOS paths in micro-cellular type settings [25]. Further channel modeling is required [26], as well as a deeper understanding of the challenges associated to the full-stack, end-to-end design of terahertz networks [5].

- **VLC** can complement Radio Frequency (RF) communications, by exploiting on the wide adoption of cheap Light Emitting Diode (LED) luminaries. LED lamps can indeed modulate signals through quick variations in light intensity, which are not visible to the human eye [27]. The research on VLC is more mature than that on Terahertz communications, partly because experimental platforms at these frequencies are more affordable and have been available for some time. A standard for VLC (i.e., IEEE 802.15.7) has also been defined; however, this technology has never been considered by the 3GPP for inclusion in a cellular network standard. VLC are non-coherent, i.e., the transmitter and receiver do not exploit the knowledge of the channel, thus the path loss is proportional to the distance raised to the power of four. Therefore, as shown in Fig. 3.3, VLC exhibit a limited coverage range. Moreover, this technology requires an illumination source (i.e., it cannot be used in the dark), and suffers from shot noise of other light sources (e.g., the sun). For these reasons, it can be mostly used indoors [27]. Moreover, this technology relies on RF for the uplink. Nonetheless, VLC could be used to introduce cellular coverage in indoor scenarios, as discussed in Sect. 2, as this is a use case that has not been fully addressed by current cellular standards. In indoor scenarios, VLC can exploit a very large unlicensed band, and be deployed without cross-interference among different rooms and with relatively cheap hardware.

Although standardization bodies are studying Terahertz and VLC solutions for future wireless systems (with the IEEE 802.15.3d and 802.15.7 standard specifications, respectively), these technologies have not yet been included in a cellular network deployments. Therefore, additional research is needed to allow 6G mobile users to transmit and receive signals in the THz and VLC frequency bands, with advances to be developed in hardware and algorithms for flexible multi-beam acquisition and tracking in NLOS environments.

Besides the addition of new frequency bands, 6G will also leverage disruptive innovation at the physical layer, and at the circuits level. The following will be key enablers for 6G:

- **Full-duplex communication stack.** A careful design of self-interference suppression circuits [28] can enable concurrent transmission and reception of wireless signals. Future cellular implementations will enable simultaneous downlink and uplink transmissions to increase the multiplexing capabilities and the overall system throughput without using additional bandwidth. 6G networks will require attentive planning for the realization of full-duplex procedures in order to avoid interference, in particular from a scheduling standpoint [28].
- **Novel channel estimation techniques.** Given the directional nature of millimeter- and Terahertz-wave communications, 6G systems will need to investigate new channel estimation techniques in these new conditions. On one side, it has been demonstrated that out-of-band information can be used to estimate the angle of arrival of the signal, thus improving the timeliness and accuracy of beam management. This can be achieved by overlaying the omnidirectional propagation profile of sub-6 GHz signals with channel

estimation at mmWaves [29]. At the same time, the sparsity of the mmWave and Terahertz channels can be leveraged to design compressive sensing techniques that estimate the channel characteristics with a reduced number of samples.

- **Sensing and network-based localization.** Even though the literature on localization and mapping is quite widespread, the use of RF signals to improve positioning has never been applied in practice to cellular networks. 6G networks will exploit a unified interface for localization and communications which can be leveraged to optimize procedures such as beamforming and handovers, or even enable new user services in the context, for example, of vehicular communications and telemedicine.

3.2 Multi-Dimensional Network Architectures

Structural network modifications will be critical to support, for example, the multi-Gbps data rates enabled by Terahertz communications. As a consequence, additional points of access to fiber, along with expanded backhaul capacity, will be necessary. Moreover, the integration of different and heterogeneous communication technologies in the same network will pose increased challenges to the management of the overall system. In this section we describe some of the main architectural innovations that will be introduced in the 6G ecosystem, as presented in Fig. 3.4 and summarized in the following paragraphs.

- **Heterogeneous access.** 6G networks will support multiple radio technologies. This feature permits multi-connectivity solutions to be applied beyond the boundaries of a cell, with the users seen as connected to the network as a whole, and not to a specific cell. This concept, which is usually referred to as "cell-less" paradigm, guarantees seamless mobility support and near-zero latency due to minimal handover overhead. The devices will then be able to automatically

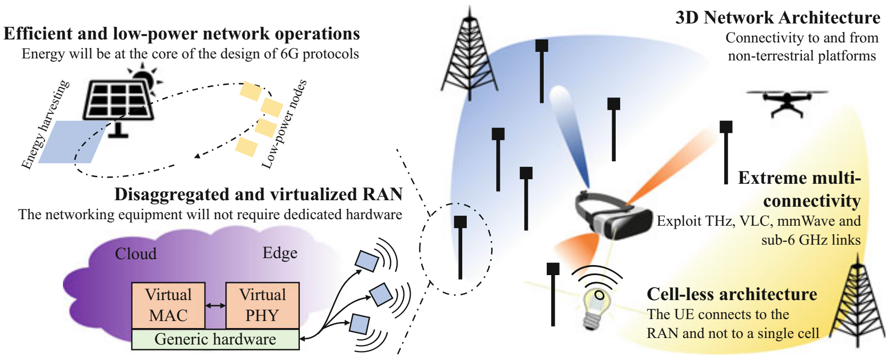

Fig. 3.4 Architectural innovations introduced in 6G networks, as illustrated in [1]

transition across heterogeneous access technologies, thereby exploiting the complementary characteristics of the different network interfaces. For example, the inherent robust nature of the sub-6 GHz layer can be leveraged for control operations, while a multi-Gbps data plane can be enabled by mmWave, Terahertz, and/or VLC links, as described in Sect. 3.1.

- **3D networks.** We envision future 6G network architectures to provide three-dimensional (3D) coverage, thereby overlaying terrestrial infrastructures with aerial/space platforms, from drones to balloons, up to satellites. Not only can these elements provide extra connectivity in the most crowded areas, e.g., during events or when terrestrial base stations are overloaded, but they can also guarantee seamless service continuity and reliability in those rural areas where fixed infrastructures are not even deployed [7]. Despite such promising opportunities, however, there are several issues to be addressed before non-terrestrial platforms can be practically deployed in wireless networks, like accurate air-to-ground and air-to-air channel modeling, topology optimization of satellite constellations and drone swarms, resource management, and energy efficiency [30].
- **Core network virtualization.** 5G networks have started the process of disaggregating once-monolithic network equipment: for example, 5G base stations can be deployed with distributed units with the lower layers of the protocol stack, and centralized units in data centers at the edge. However, the 3GPP has not yet specified how to implement virtualization, nor have existing 5G studies discussed the potential vulnerabilities associated with virtual network functions, which may indeed be subject to cyber-attacks. 6G networks will push disaggregation to its limits by virtualizing the whole protocol stack, including the Medium Access Control (MAC) and Physical (PHY) layers requiring, today, dedicated hardware implementations. This approach will allow the realization of low-cost distributed platforms with minimal baseband processing for the RF components, and will decrease the costs of networking equipment, making a massively dense deployment economically sustainable.
- **Advanced access-backhaul techniques.** For the support of terabit-per-second data rates, as envisioned in 6G, it will be fundamental to massively expand the backhaul capacity, in particular as long as Terahertz and VLC deployments, that are typically associated which a very large access point density, are concerned. The huge capacity available from 6G technologies can thus be exploited to realize self-backhauling solutions in which the radios in the base stations can offer both access and backhaul connectivity [31]. While such an approach is already under the umbrella of current 5G studies, the larger scale of 6G networks will pose new challenges and opportunities: the networks will need higher autonomous configuration capabilities, but the increase in access capacity will not need to be matched by an increase in fiber points of presence.
- **Low-power consumption.** 6G devices will be deployed in a pervasive manner to satisfy the future connectivity requirements. User terminals and networking equipment will then need to be powered with energy sources and, given the scale expected in 6G networks, it is imperative that the systems are designed

to be more efficient and less energy consuming than current networks. The main challenge associated with incorporating energy-harvesting mechanisms into 5G is the efficiency loss that takes place when converting harvested signals into electric current. One solution is to implement circuits that allow devices to be self-powered, a critical pre-requisite to enable off-grid operations or long-lived IoT sensors which are often in stand-by mode.

3.3 Predictive Models for Network Operations

The complexity introduced in the 6G architecture will likely prevent the realization of closed-form optimizations. In particular, 6G deployments will be much denser, more heterogeneous, and characterized by stricter performance requirements compared to the 5G baseline. As a consequence, while integrating intelligence in cellular networks is already under discussion within the research community, it is expected that intelligence will play a more prominent role in future 6G networks. It should be noticed that, even though the standard may not directly indicate which techniques and learning strategies should be implemented in networks, a data-driven approach still represents a promising tool that network operators and telecommunication vendors should use to meet the 6G requirements [32]. In particular, 6G research will be oriented towards the following aspects.

- **Data selection and feature extraction.** The large amount of data that will be disseminated to and from future connected devices (e.g., vehicles in a fully-autonomous framework) will overwhelm already congested communication networks. It is therefore fundamental that end terminals can discriminate the *value of information* to use their (limited) network resources for the transmission of the data contents that are considered more critical for potential receiver(s) [33, 34]. In this context, machine learning (ML) solutions can be used to compute the temporal and spatial correlation between consecutive observations, as well as to extract features from the sensors' acquisitions and predict the a-posteriori probability of a sequence given its previous history. In 6G, labeling the data for supervised learning approaches may be infeasible. Unsupervised learning, on the other hand, does not need labeling, and can be used to autonomously build representations of the complex network to perform general optimizations, going beyond the capabilities of a supervised approach. Moreover, by coupling the unsupervised representation with reinforcement learning methods it is possible to let the network fully operate in an autonomous fashion.

- **Inter-user inter-operator knowledge sharing.** With learning-based systems, mobile operators and users can share not only spectrum and infrastructures, as in traditional networks, but also learned representations of different network deployments and/or use cases, thus providing the system with improved multiplexing capabilities. Examples of applications include speeding up the network installation in new markets, or better adapting to new unexpected operational scenarios. For the development of those systems, 6G research will need to study the trade-offs associated to latency, energy consumption, and system overhead, together with the cost of on-board vs. edge-cloud-assisted processing for the data.
- **User-centric network architectures.** ML-driven networks are still in their infancy, but will represent a key component of future 6G systems. Specifically, we envision a distributed artificial intelligence paradigm aimed at realizing a user-centric network architecture. This way, it will be possible for end terminals to make autonomous network decisions depending on the results of previous operations, thus removing the overhead introduced when communicating with centralized controllers. Distributed methods can process ML algorithms with a sub-ms latency in a quasi real-time manner, thereby yielding more responsive network management.

4 Conclusions

In this chapter, we reviewed the use cases and relative key enabling technologies that we believe will characterize the future 6G framework. Table 3.1 summarizes the key challenges, potentials, and use cases of each listed technology. We make the case that 6G research can evolve the traditional wireless networking paradigms of 5G and previous generations, introducing, among other innovations, the support for Terahertz and visible light bands, cell-less and non-terrestrial architectures, and massively distributed intelligence. However, research is still needed before these technologies can be market-ready for the unforeseen digital use cases of the society of 2030 and beyond.

Table 3.1 Comparison of 6G enabling technologies and relevant use cases

Enabling technology	Potential	Challenges	Use cases
Novel wireless paradigms and frequencies above 100 GHz			
Terahertz	High data rate, small antenna size, focused beams	Circuit design, propagation loss	Pervasive connectivity, industry 4.0, teleportation
VLC	Low-cost hardware, limited interference, unlicensed spectrum	Limited coverage, need for RF uplink	Pervasive connectivity, eHealth
Full duplex	Relaying and simultaneous TX/RX	Interference management and scheduling	Pervasive connectivity, industry 4.0
Out-of-band channel estimation	Flexible multi-spectrum communications	Need for reliable frequency mapping	Pervasive connectivity, teleporting
Sensing and localization	Novel services and context-based control	Efficient multiplexing of communication and localization	eHealth, unmanned mobility, industry 4.0
Multi-dimensional network architectures			
Multi-connectivity and cell-less architecture	Seamless mobility and integration of different kinds of links	Scheduling, need for new network design	Pervasive connectivity, unmanned mobility, teleporting, eHealth
3D network architecture	Ubiquitous 3D coverage, seamless service	Modeling, topology optimization and energy efficiency	Pervasive connectivity, eHealth, unmanned mobility
Disaggregation and virtualization	Lower costs for operators for massivelydense deployments	High performance for PHY and MAC processing	Pervasive connectivity, teleporting, industry 4.0, unmanned mobility
Advanced access-backhaul integration	Flexible deployment options, outdoorto- indoor relaying	Scalability, scheduling and interference	Pervasive connectivity, eHealth
Energy-harvesting and low-power operations	Energy-efficient network operations, resiliency	Need to integrate energy source characteristics in protocols	Pervasive connectivity, eHealth

Enabling technology	Potential	Challenges	Use cases
Predictive models for network operations			
Intelligence in the network			
Learning for value of information assessment	Intelligent and autonomous selection of the information to transmit	Complexity, unsupervised learning	Pervasive connectivity, eHealth, teleporting, industry 4.0, unmanned mobility
Knowledge sharing	Speed up learning in new scenarios	Need to design novel sharing mechanisms	Pervasive connectivity, unmanned mobility
User-centric network architecture	Distributed intelligence to the endpoints of the network	Real-time and energy-efficient processing	Pervasive connectivity, eHealth, industry 4.0
Not considered in 5G		With new features/capabilities in 6G	

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