Toward 6G Networks: Use Cases and Technologies

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Abstract

Reliable data connectivity is vital for the ever increasingly intelligent, automated, and ubiquitous digital world. Mobile networks are the data highways and, in a fully connected, intelligent digital world, will need to connect everything, including people to vehicles, sensors, data, cloud resources, and even robotic agents. Fifth generation (5G) wireless networks, which are currently being deployed, offer significant advances beyond LTE, but may be unable to meet the full connectivity demands of the future digital society. Therefore, this article discusses technologies that will evolve wireless networks toward a sixth generation (6G) and which we consider as enablers for several potential 6G use cases. We provide a full-stack, system-level perspective on 6G scenarios and requirements, and select 6G technologies that can satisfy them either by improving the 5G design or by introducing completely new communication paradigms.

Introduction

Each generation of mobile technology, from the first to the fifth (5G), has been designed to meet the needs of end users and network operators, as shown in Fig. 1. However, nowadays societies are becoming more and more data-centric, data-dependent, and automated. Radical automation of industrial manufacturing processes will drive productivity. Autonomous systems are hitting our roads, oceans, and air space. Millions of sensors will be embedded into cities, homes, and production environments, and new systems operated by artificial intelligence residing in local cloud and fog environments will enable a plethora of new applications.

Communication networks will provide the nervous system of these new smart system paradigms. The demands, however, will be daunting. Networks will need to transfer much greater amounts of data at much higher speeds. Furthering a trend already started in 4G and 5G, sixth generation (6G) connections will move beyond personalized communication toward the full realization of the Internet of Things (IoT) paradigm, connecting not just people, but also computing resources, vehicles, devices, wearables, sensors, and even robotic agents [1].

5G made a significant step toward developing a low-latency tactile access network by providing new additional wireless nerve tracts through:

- New frequency bands, such as millimeter-wave (mmWave) spectrum
- Advanced spectrum usage and management in licensed and unlicensed bands
- A complete redesign of the core network

However, the rapid development of data-centric and automated processes, which require a data rate on the order of terabits per second, a latency of hundreds of microseconds, and 10^7 connections per km^2, may exceed even the capabilities of the emerging 5G systems.

The above discussion has recently motivated researchers to look into a new generation of wireless networks, that is, 6G systems, to meet the demands of a fully connected, intelligent digital world. Along these lines, the broad purpose of this article is to understand which technologies can identify 6G networks and provide more capable and vertical-specific wireless networking solutions. Specifically, the article considers several potential scenarios for future connected systems, and attempts to estimate their key requirements in terms of throughput, latency, connectivity, and other factors. Importantly, we identify several use cases that go beyond the performance of the 5G systems under development today, and demonstrate why it is important to think about the long-term evolution beyond 5G. Our analysis suggests that, in order to meet these demands, radically new communication technologies, network architectures, and deployment models will be needed. In particular, we envision:

- *Novel disruptive communication technologies:* Although 5G networks have already been designed to operate at extremely high frequencies, for example, in the mmWave bands in NR, 6G could very much benefit from even higher spectrum technologies, for example, through terahertz and optical communications.
- *Innovative network architectures:* Despite 5G advancements toward more efficient network setups, the heterogeneity of future network applications and the need for 3D coverage calls for new cell-less architectural paradigms, based on the tight integration of different communication technologies, for both access and backhaul, and on the disaggregation and virtualization of the networking equipment.
- *Integrating intelligence in the network:* We expect 6G to bring intelligence from central-

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Th y requirement sub-millisecond, and thousands of synchronized view angles will be necessary, as opposed to the few required for VR/AR. Moreover, to fully realize an immersive remote experience, all five human senses are destined to be digitized and transferred across future networks, increasing the overall target data rate.

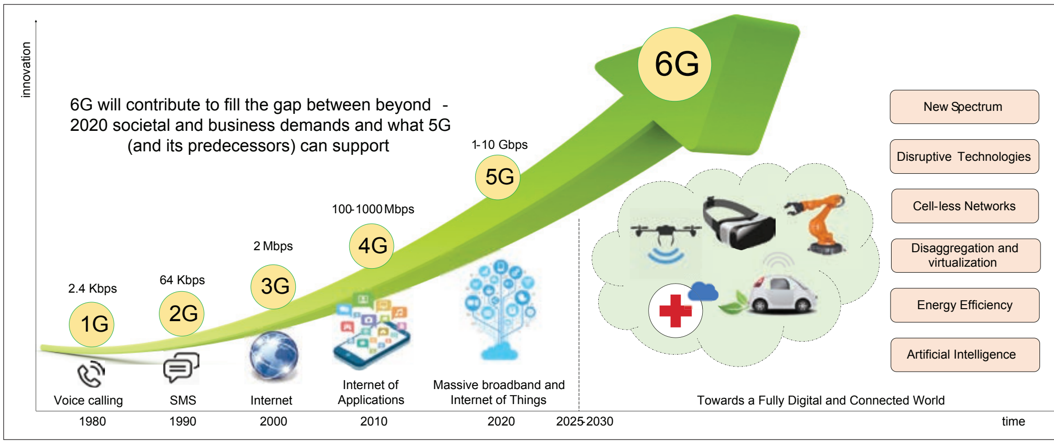

Figure 1. Evolution of cellular networks, from 1G to 6G, with a representative application for each generation.

ized computing facilities to end terminals, thereby providing concrete implementation to distributed learning models that have been studied from a theoretical point of view in a 5G context. Unsupervised learning and knowledge sharing will promote real-time network decisions through prediction.

Prior publications (most notably [2, 3]) have discussed 6G communications. This article distinctively adopts a systematic approach in analyzing the research challenges associated with 6G networks, providing a full-stack perspective, with considerations related to spectrum usage, physical, medium access, and higher layers, and network architectures and intelligence for 6G. We transfer into our work a multifaceted critical spirit too, having selected, out of several possible innovations, the solutions that in our view show the highest potential for future 6G systems. While some of them appear to be incremental, we believe that the combination of breakthrough technologies and evolution of current networks deserves to be identified as a new generation of mobile networks, as these solutions have not been thoroughly addressed or cannot be properly included in current 5G standards developments, and therefore will not be part of commercial 5G deployments. We expect our investigation to promote research efforts toward the definition of new communication and networking technologies to meet the boldest requirements of 6G use cases.

6G Use Cases

5G presents trade-offs on latency, energy, costs, hardware complexity, throughput, and end-to-end reliability. For example, the requirements of mobile broadband and ultra-reliable low-latency communications are addressed by different configurations of 5G networks. 6G, on the contrary, will be developed to jointly meet stringent network demands (e.g., ultra-high reliability, capacity, efficiency, and low latency) in a holistic fashion, in view of the foreseen economic, social, technological, and environmental context of the 2030 era.

In this section, we review the characteristics and foreseen requirements of use cases that, for their generality and complementarity, are believed to well represent future 6G services. Figure 2 provides a comprehensive view on the scenarios in terms of different key performance indicators (KPIs).

Augmented Reality and Virtual Reality

4G systems unlocked the potential of video-over-wireless, one of the most data-hungry applications at the time. The increasing use of streaming and multimedia services currently justifies the adoption of new spectrum (i.e., mmWaves) to guarantee higher capacity in 5G. However, this multi-gigabit-per-second opportunity is attracting new applications that are more data-heavy than bi-dimensional multimedia content: 5G will trigger the early adoption of augmented/virtual reality (AR/VR). Then, just like video-over-wireless saturated 4G networks, the proliferation of AR/VR applications will deplete the 5G spectrum, and require a system capacity above 1 Tb/s, as opposed to the 20 Gb/s target defined for 5G [1]. Additionally, to meet the latency requirements that enable real-time user interaction in the immersive environment, AR/VR cannot be compressed (coding and decoding is a time-consuming process); thus, the per-user data rate needs to touch the gigabit-per-second, in contrast to the more relaxed 100 Mb/s 5G target.

Holographic Telepresence (Teleportation)

The human tendency to connect remotely with increasing fidelity will pose severe communication challenges in 6G networks. Reference [4] details the data rate requirements of a 3D holographic display: a raw hologram, without any compression, with colors, full parallax, and 30 fps, would require 4.32 Tb/s. The latency requirement will hit sub-millisecond, and thousands of synchronized view angles will be necessary, as opposed to the few required for VR/AR. Moreover, to fully realize an immersive remote experience, all five human senses are destined to be digitized and transferred across future networks, increasing the overall target data rate.

eHealth

6G will revolutionize the healthcare sector, eliminating time and space barriers through remote surgery and guaranteeing healthcare workflow optimizations. Besides the high cost, the current major limitation is the lack of real-time tactile feedback [5]. Moreover, the proliferation of eHealth services will challenge the ability to meet their stringent quality of service (QoS) requirements, that is, continuous connection availability (99.99999 percent reliability), ultra-low latency (sub-millisecond), and mobility support.

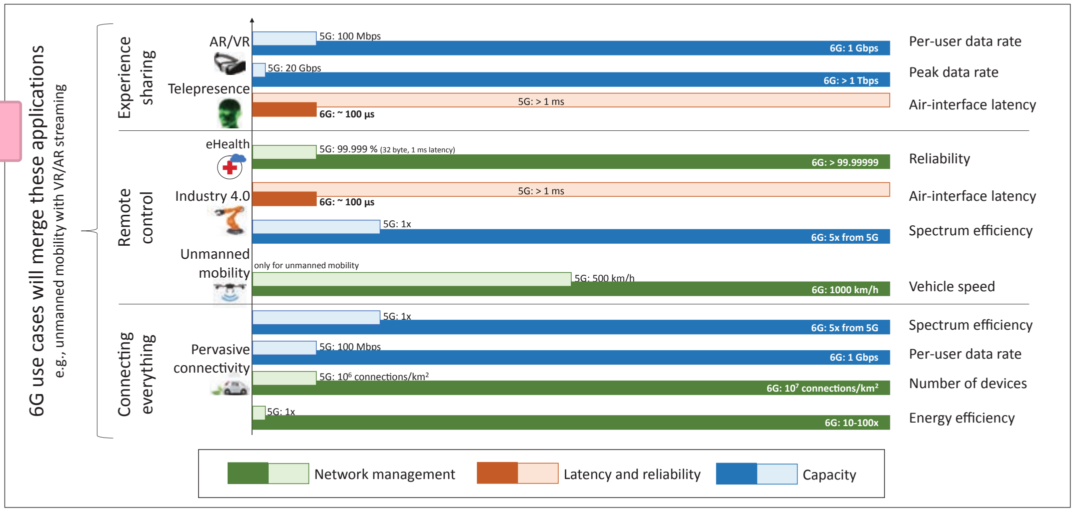

Figure 2. Representation of multiple KPIs of 6G use cases, together with the improvements with respect to 5G networks, using data from [1–9].

Overcoming the boundaries between the real factory and the cyber computational space will enable Internet-based diagnostics, maintenance, operation, and direct machine communications in a cost-effective, flexible and efficient way.

The increased spectrum availability, combined with the refined intelligence of 6G networks, will guarantee these KPIs, together with 5–10× gains in spectral efficiency [1].

Pervasive Connectivity

Mobile traffic is expected to grow three-fold from 2016 to 2021, pushing the number of mobile devices to the extreme, with 10^7 devices per km^2 in dense areas (up from 10^6 in 5G) [1] and more than 125 billion devices worldwide by 2030. 6G will connect personal devices, sensors (to implement the smart city paradigm), vehicles, and so on. This will stress already congested networks, which will not provide connectivity to every device while meeting the requirements of Fig. 2. Moreover, 6G networks will require a higher overall energy efficiency (10–100× with respect to 5G) to enable scalable, low-cost deployments with low environmental impact and better coverage. Indeed, while 80 percent of mobile traffic is generated indoors, 5G cellular networks, which are being mainly deployed outdoors and may be operating in the mmWave spectrum, will hardly provide indoor connectivity as high-frequency radio signals cannot easily penetrate dielectric materials (e.g., concrete). 6G networks will instead provide seamless and pervasive connectivity in a variety of different contexts, matching stringent QoS requirements in outdoor and indoor scenarios with a cost-aware and resilient infrastructure.

Industry 4.0 and Robotics

6G will fully realize the Industry 4.0 revolution started with 5G, that is, the digital transformation of manufacturing through cyber physical systems and IoT services. Overcoming the boundaries between the real factory and the cyber computational space will enable Internet-based diagnostics, maintenance, operation, and direct machine communications in a cost-effective, flexible and efficient way [6]. Automation comes with its own set of requirements in terms of reliable and isochronous communication [7], which 6G is positioned to address through the disruptive set of technologies we describe later. For example, industrial control requires real-time operations with guaranteed microsecond delay jitter, and gigabit-per-second peak data rates for AR/VR industrial applications (e.g., for training, inspection).

Unmanned Mobility

The evolution toward fully autonomous transportation systems offers safer traveling, improved traffic management, and support for infotainment, with a market of US$7 trillion [8]. Connecting autonomous vehicles demands unprecedented levels of reliability and low latency (i.e., above 99.99999 percent and below 1 ms, respectively), even in ultra-high-mobility scenarios (up to 1000 km/h) to guarantee passenger safety, a requirement that is hard to satisfy with existing technologies. Moreover, the increasing number of sensors per vehicle will demand increasing data rates (with terabytes generated per driving hour [9]), beyond current network capacity. In addition, flying vehicles (e.g., drones) represent a huge potential for various scenarios (e.g., construction, first responders). Swarms of drones will need improved capacity for expanding Internet connectivity. In this perspective, 6G will pave the way for connected vehicles through advances in hardware, software, and the new connectivity solutions we discuss later.

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.

6G Enabling Technologies

In this section, we present the technologies that are rapidly emerging as enablers of the KPIs for the 6G scenarios foreseen above. In particular, Table 1 summarizes potentials and challenges of each proposed technological innovation and suggests which of the use cases introduced earlier they empower. Although some of these innovations have already been discussed in the context of 5G, they were deliberately left out of early 5G standards developments (i.e., Third Generation Partnership Project [3GPP] NR Releases 15 and 16) and will likely not be implemented in commercial 5G deployments because of technological limitations or because markets are not mature enough to support them. In this section we con-

Enabling Technology	Potential	Challenges	Use cases
		New spectrum	
Terahertz	High bandwidth, small antenna size, focused beams	Circuit design, high propagation loss	Pervasive connectivity, industry 4.0, holographic telepresence
VLC	Low-cost hardware, low interference, unlicensed spectrum	Limited coverage, need for RF uplink	Pervasive connectivity, eHealth
		Novel PHY techniques	
Full duplex	Continuous TX/RX and relaying	Management of interference, scheduling	Pervasive connectivity, industry 4.0
Out-of-band channel estimation	Flexible multi-spectrum communications	Need for reliable frequency mapping	Pervasive connectivity, holographic telepresence
Sensing and localization	Novel services and context-based control	Efficient multiplexing of communication and localization	eHealth, unmanned mobility, industry 4.0
		Innovative 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, holographic telepresence, 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 massively-dense deployments	High performance for PHY and MAC processing	Pervasive connectivity, holographic telepresence, industry 4.0, unmanned mobility
Advanced access-backhaul integration	Flexible deployment options, outdoor-to-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
		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, holographic telepresence, 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	

Table 1. Comparison of 6G enabling technologies and relevant use cases.

sider physical layer breakthroughs, new architectural and protocol solutions, and finally disruptive applications of artificial intelligence.

Disruptive Communication Technologies

A new generation of mobile networks is generally characterized by a set of novel communication technologies that provide unprecedented performance (e.g., in terms of available data rate and latency) and capabilities. For example, massive multiple-input multiple-output (MIMO) and mmWave communications are both key enablers of 5G networks. In order to meet the requirements described earlier, 6G networks are expected to rely on conventional spectrum (i.e., sub-6 GHz and mmWaves) but also on frequency bands that have not yet been considered for cellular standards, namely the terahertz band and visible light communications (VLC). Figure 3 represents the path loss for each of these bands in typical deployment scenarios in order to highlight the differences and opportunities that each portion of the spectrum can exploit. In the following paragraphs, we focus on the two novel spectrum bands that will be used in 6G.

Terahertz Communications: These operate between 100 GHz and 10 THz [10] and, compared to mmWaves, bring to the extreme the potential of high-frequency connectivity, enabling data rates on the order of hundreds of gigabits per second, in line with the boldest 6G requirements. On the other side, the main issues that have prevented the adoption of terahertz links in commercial systems so far are propagation loss, molecular absorption, high penetration loss, and engineering challenges for antennas and radio frequency (RF) circuitry. As for mmWaves, the propagation loss can be compensated using directional antenna arrays, also enabling spatial multiplexing with limited interference. Furthermore, terahertz communication performance can be maximized by operating in frequency bands not severely affected by molecular absorption [10], as shown in Fig. 3. Finally, such high frequencies, when limited to indoor-to-indoor scenarios, enable new kinds of ultra-small-scale electronic packaging solutions for the RF and antenna circuitry.

VLC: These have been proposed to complement RF communications by piggybacking on the wide adoption of cheap light emitting diode (LED) luminaries. These devices can indeed quickly switch between different light intensities to modulate a signal that can be transmitted to a proper receiver [12]. The research on VLC is

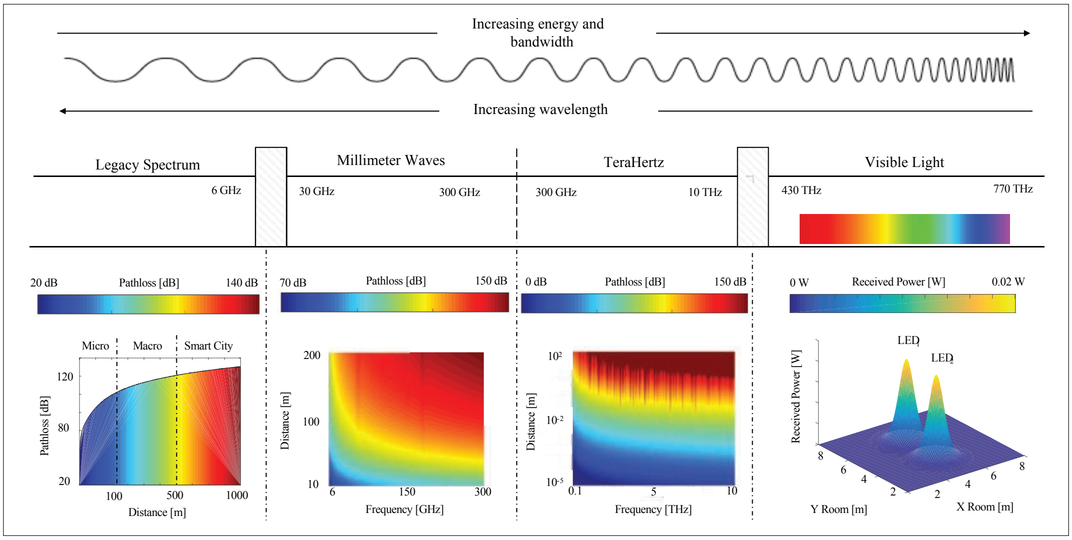

Figure 3. Path loss for sub-6 GHz, mmWave, and terahertz bands, and received power for VLC. The sub-6 GHz and mmWave path loss follows the 3GPP models considering both line-of-sight (LoS) and non-LoS (NLoS) conditions, while LoS-only is considered for terahertz [10] and VLC [11].

The density and high access data rate of terahertz communications will increase the capacity demands on the underlying transport network, which has to provide both more points of access to fiber and higher capacity than today's backhaul networks. Moreover, the wide range of different communication technologies available will increase the heterogeneity of the network, which will need to be managed.

more mature than that on terahertz communications, also thanks to lower cost of experimental platforms. As reported in Fig. 3, VLC have limited coverage range, require an illumination source, and suffer from shot noise from other light sources (e.g., the sun), and thus can be mostly used indoors [12]. Moreover, they need to be complemented by RF for the uplink. Nonetheless, VLC could be used to introduce cellular coverage in indoor scenarios, which, as mentioned previously, is a use case that has not been properly addressed by cellular standards.

Although standardization bodies are promoting study items that are oriented toward the investigation of terahertz and VLC solutions for future wireless systems (i.e., IEEE 802.15.3d and 802.15.7, respectively), these technologies have not yet been included in a cellular network standard, and will be targeting beyond 5G use cases. Moreover, additional research is still required to enable 6G mobile users to operate in the terahertz and VLC spectra, including hardware and algorithms for flexible multi-beam acquisition and tracking in non-line-of-sight (NLoS) environments.

Besides the new spectrum, 6G will also transform wireless networks by leveraging a set of technologies that have been enabled by recent physical layer and circuit research, but are not part of 5G. The following will be key enablers for 6G.

Full-Duplex Communication Stack: With full-duplex communications, the transceivers will be capable of receiving a signal while also transmitting, thanks to carefully designed self-interference-suppression circuits [13]. Practical full-duplex deployments require innovations in antenna and circuit design to reduce the crosstalk between transmitter and receiver circuits in a wireless device; thus, they have not been included in current cellular network specifications. Future technology advancements, however, will enable concurrent downlink and uplink transmission to increase the multiplexing capabilities and the overall system throughput without using additional bandwidth. Nonetheless, 6G networks will need careful planning for full-duplex procedures and deployments to avoid interference, as well as novel resource scheduler designs [13].

Novel Channel Estimation Techniques (e.g., Out-of-Band Estimation and Compressed Sensing): Channel estimation for directional communications will be a key component of communications at mmWaves and terahertz frequencies. However, it is difficult to design efficient procedures for directional communications, considering multiple frequency bands and possibly a very large bandwidth. Therefore, 6G systems will need new channel estimation techniques. For example, out-of-band estimation (e.g., for the angular direction of arrival of the signal) can improve the reactiveness of beam management by mapping the omnidirectional propagation of sub-6 GHz signals to the channel estimation for mmWave frequencies [14]. Similarly, given the sparsity in terms of angular directions of mmWave and terahertz channels, it is possible to exploit compressive sensing to estimate the channel using a reduced number of samples.

Sensing and Network-Based Localization: The usage of RF signals to enable simultaneous localization and mapping has been widely studied, but such capabilities have never been deeply integrated with the operations and protocols of cellular networks. 6G networks will exploit a unified interface for localization and communications to improve control operations, which can rely on context information to shape beamforming patterns, reduce interference, predict handovers, and offer innovative user services (e.g., for vehicular and eHealth applications).

Innovative Network Architectures

The disruption brought by the communication technologies described earlier will enable a new 6G network architecture, but also potentially require structural updates with respect to current mobile network designs. For example, the density and the high access data rate of terahertz communications will increase the capacity demands on the underlying transport network, which has to provide both more points of access to fiber and a higher capacity than today's backhaul networks. Moreover, the

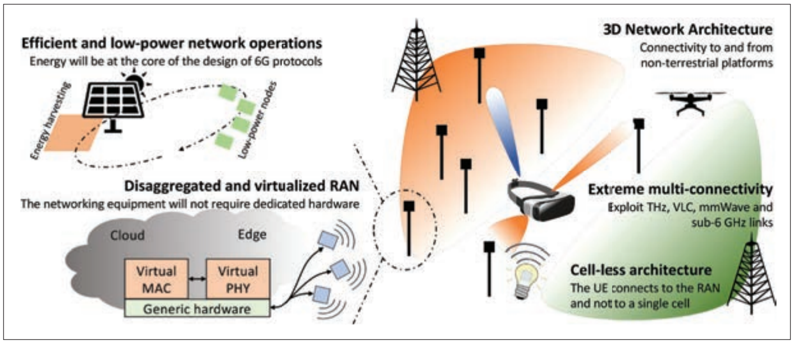

Figure 4. Architectural innovations introduced in 6G networks.

wide range of different communication technologies available will increase the heterogeneity of the network, which will need to be managed.

The main architectural innovations that 6G will introduce are described in Fig. 4. In this context, we envision the introduction and/or deployment of the following paradigms.

Tight integration of multiple frequencies and communication technologies and cell-less architecture: 6G devices will support a number of heterogeneous radios in the devices. This enables multi-connectivity techniques that can extend the current boundaries of cells, with users connected to the network as a whole (i.e., through multiple complementary technologies) and not to a single cell. The cell-less network procedures will guarantee seamless mobility support without overhead due to handovers (which might be frequent when considering systems at terahertz frequencies), and will provide QoS guarantees that are in line with the most challenging mobility requirements envisioned for 6G, as in the vehicular scenarios. The devices will be able to seamlessly transition among different heterogeneous links (e.g., sub-6 GHz, mmWave, terahertz, and VLC) without manual intervention or configuration. Finally, according to the specific use case, the user may also concurrently use different network interfaces to exploit their complementary characteristics, for example, the sub-6 GHz layer for control, and a terahertz link for the data plane.

3D Network Architecture: 5G networks (and previous generations) have been designed to provide connectivity for an essentially bi-dimensional space, that is, network access points are deployed to offer connectivity to devices on the ground. On the contrary, we envision future 6G heterogeneous architectures to provide three-dimensional coverage, thereby complementing terrestrial infrastructures with non-terrestrial platforms (e.g., drones, balloons, and satellites). Moreover, these elements could also be quickly deployed to guarantee seamless service continuity and reliability, for example, in rural areas or during events, avoiding the operational and management costs of always-on, fixed infrastructures. Despite such promising opportunities, there are various challenges to be solved before flying platforms can effectively be used in wireless networks, for example, air-to-ground channel modeling, topology and trajectory optimization, resource management, and energy efficiency.

Disaggregation and Virtualization of the Networking Equipment: Even though networks have recently started to transition toward the disaggregation of once-monolithic networking equipment, the 3GPP does not directly specify how to introduce virtualization concepts. Moreover, current 5G studies have not yet addressed the challenges related to the design of disaggregated architectures that can operate under the higher control latency that might be introduced by centralization, and to the security of virtualized network functions, which could be subjected to cyber-attacks. 6G networks will bring disaggregation to the extreme by virtualizing medium access control (MAC) and physical (PHY) layer components, which currently require dedicated hardware implementations, and realizing low-cost distributed platforms with just the antennas and minimal processing. This will decrease the cost of networking equipment, making massively dense deployment economically feasible.

Advanced Access-Backhaul Integration: The massive data rates of the new 6G access technologies will require adequate growth of the backhaul capacity. Moreover, terahertz and VLC deployments will increase the density of access points, which need backhaul connectivity to their neighbors and the core network. The huge capacity of 6G technologies can thus be exploited for self-backhauling solutions, where the radios in the base stations provide both access and backhaul. While a similar option is already being considered for 5G, the scale of 6G deployments will introduce new challenges and opportunities; for example, the networks will need higher autonomous configuration capabilities.

Energy-Harvesting Strategies for Low Power Consumption Network Operations: Incorporating energy-harvesting mechanisms into 5G infrastructures currently faces several issues, including coexistence with the communications, and efficiency loss when converting harvested signals to electric current. Given the scale expected in 6G networks, it is necessary to design systems where both the circuitry and the communication stack are developed with energy awareness in mind. One option is using energy-harvesting circuits to allow devices to be self-powered, which could be critical, for example, to enable off-grid operations, long-lasting IoT devices and sensors, or long stand-by intervals for devices and equipment that are rarely used.

Integrating Intelligence in the Network

The complexity of 6G communication technologies and network deployments will probably prevent closed-form and/or manual optimizations. While intelligent techniques in cellular networks are already being discussed for 5G, we expect 6G deployments to be much denser (i.e., in terms of number of access points and users) and more heterogeneous (in terms of integration of different technologies and application characteristics), and have stricter performance requirements with respect to 5G. Therefore, intelligence will play a more prominent role in the network, going beyond the classification and prediction tasks that are being considered for 5G systems. Notice that the standard may not specify the techniques and learning strategies to be deployed in networks, but data-driven approaches can be seen as tools that network vendors and operators can use to meet the 6G requirements [15]. In particular, 6G research will be oriented toward the following aspects.

Learning Techniques for Data Selection and Feature Extraction: The large volume of data generated by future connected devices (e.g., sensors in autonomous vehicles) will put a strain on communication technologies, which could not guarantee the required quality of service. It is therefore fundamental to discriminate the value of information to maximize the utility for the end users with (limited) network resources. In this context, machine learning (ML) strategies can evaluate the degree of correlation in observations, or extract features from input vectors and predict the a posteriori probability of a sequence given its entire history. Moreover, in 6G, unsupervised and reinforcement learning approaches do not need labeling and can be used to operate the network in a truly autonomous fashion.

Inter-User Inter-Operator Knowledge Sharing: Spectrum and infrastructure sharing is beneficial in cellular networks to maximize the multiplexing capabilities. With learning-driven networks, operators and users can also share learned/processed representations of specific network deployments and/or use cases, for example, to speed up the network configuration in new markets or to better adapt to new unexpected operational scenarios. The trade-offs in latency, power consumption, system overhead, and cost will be studied in 6G for both onboard and edge-cloud-assisted solutions.

User-Centric Network Architecture: ML-driven networks are still in their infancy, but will be a fundamental component of complex 6G systems, which envision distributed artificial intelligence, to implement a fully user-centric network architecture. In this way, end terminals will be able to make autonomous network decisions based on the outcomes of previous operations without communication overhead to and from centralized controllers. Distributed methods can process ML algorithms in real time, that is, with a sub-ms latency, as required by several 6G services, thereby yielding more responsive network management.

While intelligent techniques in cellular networks are already being discussed for 5G, we expect 6G deployments to be much denser and more heterogeneous, and have stricter performance requirements with respect to 5G. Therefore, intelligence will play a more prominent role in the network, going beyond the classification and prediction tasks that are being considered for 5G systems.

Conclusions

In this article, we review use cases and technologies that we believe will characterize 6G networks. Table 1 summarizes the main challenges, potentials, and use cases of each enabling technology. 6G wireless research can disrupt the traditional cellular networking paradigms that still exist in 5G, introducing, for example, support for terahertz and visible light spectra, cell-less and aerial architectures, and massive distributed intelligence, among others. These technologies, however, are not market-ready: this represents a unique opportunity for the wireless research community to foster innovations that will enable unforeseen digital use cases for the society of 2030 and beyond.

Acknowledgments

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Biographies

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