Towards 6G Networks: Use Cases and Technologies

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***Abstract*—As the digital world becomes increasingly intelligent, automated and ubiquitous, the flow of data becomes ever more vital. Mobile wireless networks are the data highways, and in a fully connected, intelligent digital world, they will need to connect everything from people, vehicles, sensors, data, cloud resources and even robotic agents. Fifth generation (5G) wireless networks that are being released soon offer significant advances, but may be unable to meet the full connectivity demands of emerging systems. This paper envisions how 6G systems can be developed to address the needs of smart networks of the future. The article considers several potential 6G use cases and attempts to provide estimates on requirements to guide design. The demands are daunting, but several promising technologies that can provide the basis for 6G systems are also surveyed.**

I. Introduction

From 1G to 5G, passing through Universal Mobile Telecommunication Systems (UMTS) and Long Term Evolution (LTE) innovations, each generation of mobile technology has been designed to meet the needs of network operators and final consumers, as shown in Fig. 1. However, nowadays societies are becoming ever 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 food production environments, and new systems operated by artificial intelligence which often will reside in new local 'clouds' and 'fog' environments will create a plethora of new applications.

Communications networks will provide the nervous system of these new smart system paradigms. But, the demands will be daunting. Networks will need to transfer much greater amounts of data, at much higher speeds. Connections will move beyond personalized communication to machine-type communication, connecting not just people, but data, computing resources, vehicles, devices, wearables, sensors and even robotic agents.

5G made a significant step towards developing a low latency tactile access network, by providing new additional wireless nerve tracts through (i) new frequency bands (e.g., the millimeter wave (mmWave) spectrum), (ii) advanced spectrum usage and management, and (iii) seamless integration of licensed and unlicensed bands. Yet, the rapid of development of data-centric and automated processes may exceed even the capabilities of emerging 5G systems.

The above discussion has recently motivated researchers to look into a new generation of wireless systems, i.e., sixth generation (6G) systems, to meet the demands for a fully connected, intelligent digital world. Along these lines, the broad purpose of this paper is to understand how future 6G systems can be developed. Specifically, the paper considers several potential applications for future connected systems and attempts to estimate the key requirements in terms of throughput, latency, connectivity and other factors. Importantly, we identify several use cases that go beyond the performance of 5G systems under development today and demonstrate why it is important to think about the long term evolutions of 5G. Our analysis suggests that, in order to meet these demands, radically new underlying communication technologies, network architectures and deployments models will be needed. In particular, we envision:

- *Novel disruptive communication technologies:* although 5G networks have already been designed to operate at very high frequencies, e.g., in the mmWave bands in NR, 6G networks could very much benefit from even higher spectrum technologies, e.g., through terahertz and optical communications.
- *Innovative network architectures:* despite 5G advancements towards more efficient network setups, the heterogeneity of requirements of future network applications call for new architectural paradigms based on tight orchestration among different communication technologies, disaggregation and virtualization of the networking equipment, and advanced access-backhaul integration.
- *Integrating Intelligence in the Network:* we expect 6G to bring intelligence from centralized computing facilities to every terminal in the network. Unsupervised learning, together with inter-user inter-operator knowledge sharing, will promote real-time network decisions through prediction.

Therefore, in this paper, we survey emerging technologies that are not available in networks today but have significant potential for future 6G systems, including developments at all layers of the protocol stack, from physical layer communication methods to networking design. We also study evolutions of network designs that, even though they were in part already proposed for 5G, need new architectural innovations to meet the boldest requirements of 6G use cases.

II. 6G Potential Applications

5G technologies have always been associated with trade-offs which involve latency, power consumption, deployment costs, hardware complexity, experienced throughput, end-to-end reliability, and communication resilience. On the contrary, the market demands of 2030 and beyond will introduce new applications, with more stringent requirements (in terms of ultra-high reliability, capacity, energy efficiency, and low latency) which may saturate the capacity of traditional technologies for wireless systems. 6G will contribute to fill this gap.

In this section, we review the proprieties, characteristics and foreseen requirements of applications that, for their generality and complementarity, are generally believed to be

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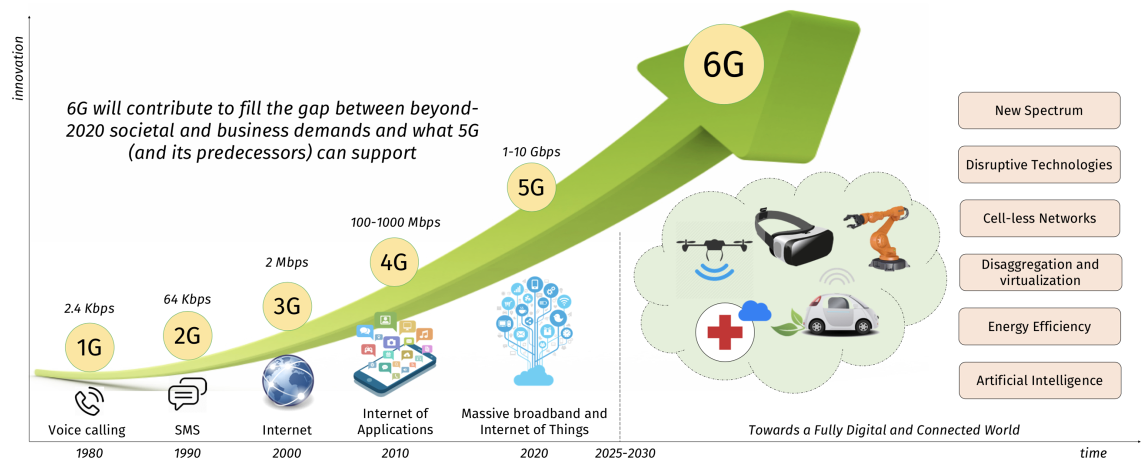

Fig. 1: Evolution of cellular network generation, from 1G to the disruption which are expected in 6G networks. Each generation is represented by the most relevant/representative application. As it can be seen, 6G targets the support of multiple applications that will enable the future digital society.

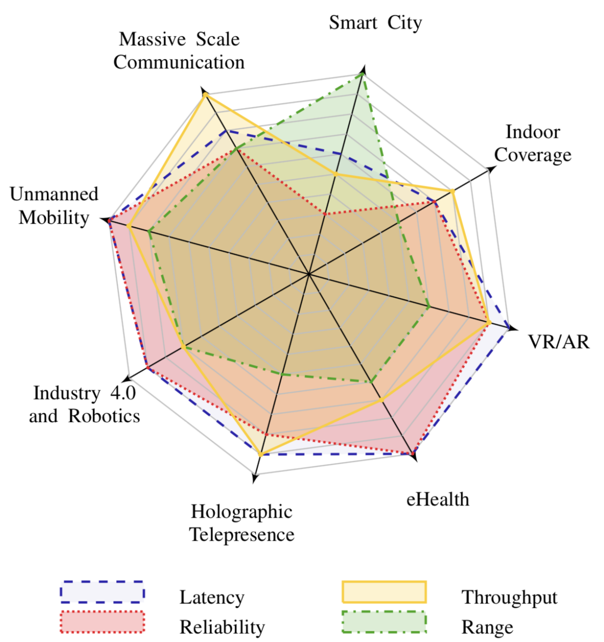

Fig. 2: Representation of the requirements (according to multiple Key Performance Indicators (KPIs)) of different 6G use cases.

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 that 5G is supposed to be released). Fig. 2 provides a comprehensive point of view on application requirements in terms of different KPIs.

Massive scale communications: Although 5G networks are designed to support more than 1’000’000 connections per km^2, mobile traffic will grow 3-fold from 2016 to 2021, thereby pushing the number of mobile devices to the extreme (according to some estimates, there will be more than 125 billion connected devices worldwide by 2030 [1]). This will likely stress already congested networks, which will not guarantee the required Quality of Service (QoS). Moreover, the multi-Mbps data rates that the new 5G wireless systems will attempt to offer will likely not comply with the requirements of a society that is now completely data-driven and needs near-instant ultra-high-throughput connectivity, as shown in Fig. 2. 6G technologies should encompass capacity expansion strategies to offer high throughput and continuous connectivity to the users, even when civil communication infrastructures may be compromised (e.g., after natural disasters).

Augmented Reality (AR) and Virtual Reality (VR): AR and VR over wireless will become a key application in various use cases including, but not limited to, (i) education and training, (ii) gaming, (iii) workspace communication, (iv) entertainment. VR/AR applications will face unprecedented challenges in terms of increased quality of immersion, increased per-user capacity, sub-ms latency and uniform quality of experience (also at cell edge). Mobile edge, cloud and fog computing techniques will bring intelligence to end users, to support efficient data dissemination while fulfilling network’s heterogeneous requirements and backhaul/fronthaul limitations. 6G will develop along these lines.

Holographic Telepresence (Teleportation): The human tendency to remotely connect with an increasing amount of digital accuracy will pose severe communications challenges in next generation network infrastructures. The authors in [2] explore a 3D holographic display and its data transmission requirement: a raw hologram, without any optimization nor compression, with colors, full parallax, and 30 fps, would require a daunting 4.32 Tbps data rate. The latency requirement will hit the sub-ms, and thousands of synchronized view angles will be necessary, as opposed to the 2 tiles required for 4K/8K HD audio/video and the 12 tiles required for VR/AR. Moreover, to fully realize an immersive remote experience, all the 5 human senses are destined to be digitized and transferred across future networks, increasing the overall target data rate.

eHealth: 6G will revolutionize the health-care sector, e.g., eliminating time and space barriers through remote surgery and guaranteeing health-care workflow optimizations. Besides the high cost, the major limitation preventing the application of current communication technologies in healthcare is the lack of real-time tactile feedback [3]. Moreover, QoS expectations for eHealth services (i.e., continuous connection availability, ultra-low data delivery latency, ultra-high reliability, and mobility support) will unlikely be jointly fulfilled by 5G systems, due to the increased inherent variability of the mmWave channel and the congestion below 6 GHz. 6G enhancements will unleash the potential of eHealth applications through innovations like mobile edge computing, virtualization and artificial intelligence.

Indoor coverage: While 80% of the mobile traffic is generated indoor, 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. 5G densification through femtocells, or Distributed Antenna Systems (DASs), which were proposed as a solution for indoor connectivity, present scalability issues and high deployment and management costs for operators. 6G should target cost-aware, efficient indoor connectivity solutions that can be autonomously deployed by end-users and managed by the network operators, for example through ultra-high-capacity wireless relays coupled with indoor communications in the visible light spectrum [4].

Industry 4.0 and Robotics: 6G will foster the Industry 4.0 revolution started with 5G, i.e., the digital transformation of manufacturing through Cyber Physical Systems (CPS) and Internet of Things (IoT) services. In particular, CPSs will break the boundaries between the physical factory dimension and the cyber computational space, thus enabling, among other things, Internet-based diagnostics, maintenance, operation, and direct Machine to Machine (M2M) communications in a cost-effective, flexible and efficient way [5]. Automation comes with its own set of requirements in terms of reliable and isochronous communication [6], which 6G is positioned to address though new semiconductor and integrated circuit (IC) innovations, e.g., by developing new kind of terahertz scale electronic packaging solutions.

Smart city: 6G will accelerate the adoption of solutions for smart cities, targeting life quality improvements, environmental monitoring, traffic control and city management automation [7]. These services build upon data generated by low-cost and low-energy consuming sensors, which efficiently interact with each other and their surrounding environment. Current cellular systems have been mainly developed for broadband applications, with ad hoc configurations for M2M traffic. Conversely, 6G will seamlessly include support for user-centric machine to machine communication, providing native support for smart cities in a cost-effective way. 6G will also promote ultra-long battery lifetime combined with energy harvesting approaches, a research challenge that 5G and its predecessors have, so far, largely disregarded.

Unmanned mobility: The automotive industry is rapidly evolving towards fully autonomous transportation systems, offering safer traveling, improved traffic management, and support for infotainment applications, with market estimates in the order of 7 trillions USD [8]. The design and deployment of connected and autonomous vehicles (CAVs) is still challenging: with the safety of passengers at stake, unprecedented levels of communication reliability and low end-to-end latency (i.e., above 99.9999% and below 1 ms, respectively) are expected, even in ultra-high mobility scenarios (up to an impressive 1000 km/h). Moreover, cars will be equipped with an increasing number of sensors (more than 200 per vehicle by 2020) which will demand increasing data rates (in the order of terabytes per driving hour [9]), saturating the capacity of traditional technologies. In addition, flying vehicles (e.g., drones) represent a huge market potential for various use cases such as construction, agriculture, and first responders. Swarms of drones will need improved capacity for expanding Internet connectivity. In this perspective, 6G will pave the way for the coming era of connected vehicles through advances in hardware and software as well as the pioneering connectivity solutions the we will discuss in Sec. III.

III. 6G Enabling Technologies

In this Section we will describe the technological innovations that are expected to enable the 6G transformation and meet the KPIs for the 6G applications that we described in Fig. 2. We will consider physical layer breakthroughs in Sec. III-A, new architectural and protocol solutions in Sec. III-B, and finally disruptive applications of artificial intelligence in Sec. III-C. Table I summarizes the main technological innovations that could be introduced in 6G networks, considering their potential, the associated challenges and which of the use cases introduced in Sec. II they empower.

A. 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, 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 that we described in Sec. II, 6G networks are expected to rely on conventional spectrum (i.e., sub-6 GHz and mmWaves) but also on frequency bands that have not been considered yet for cellular standards, namely the terahertz band and Visible Light Communications (VLC). Fig. 3 represents the pathloss for each of these bands, in typical deployment scenarios, in order to highlight the differences and the opportunities that each portion of the spectrum can exploit. In the following paragraphs, we will focus on the two novel spectrum bands that will be used in 6G, namely:

- **Terahertz communications** exploit the frequency bands between 100 GHz and 10 THz [10]. With respect to the millimeter waves used in 5G, terahertz brings to the extreme the potentials and challenges of high-frequency communications. The main issues that prevented the adoption of terahertz links in commercial systems are the propagation loss, the molecular absorption, the high penetration loss and the engineering of antennas and RF circuitry. As for mmWaves, the propagation loss can be compensated using directional antenna arrays, also enabling spatial multiplexing with limited interference. Furthermore, some frequencies in the terahertz spectrum are affected by an additional loss due to atmospheric

TABLE I: Comparison of 6G enabling technologies and relevant use cases.

	Potential	Challenges	Use cases
		New Spectrum	
Terahertz	High bandwidth, small antenna size, focused beams	Circuit design, high propagation loss	Massive scale communications, industry 4.0, holographic telepresence, indoor
VLC	Low-cost hardware, low interference, unlicensed spectrum	Limited coverage, need for RF uplink	Indoor coverage, smart city
		Novel PHY techniques	
Full duplex	Enable continuous TX and RX and relaying	Management of interference, scheduling	Massive scale communications, industry 4.0, indoor
Out-of-band channel estimation	Enable flexible multi-spectrum communications	Need for reliable frequency mapping	Massive scale communications, holographic telepresence, indoor
Sensing and localization	Novel services and context-based control	Efficient multiplexing of communication and localization	Indoor, eHealth, unmanned mobility, industry 4.0
		Innovative Network Architectures	
Cell-less architecture and multi-connectivity	Seamless mobility and integration of different kinds of links	Scheduling, need for new network design	Massive scale communications, unmanned mobility, holographic telepresence, eHealth
Disaggregation and virtualization	Lower costs for operators to enable massively-dense and edge deployments	High performance for PHY and MAC processing	Massive scale communications, holographic telepresence, eHealth, industry 4.0, smart city, unmanned mobility
Advanced access-backhaul integration	Flexible deployment options, outdoor-to-indoor relaying	Scalability, scheduling and interference	Indoor, massive scale communications, smart city, eHealth
Energy-harvesting and low-power operations	Energy-efficient network operations, resiliency	Need to integrate energy source characteristics in protocols	Smart city, eHealth
		Intelligence in the network	
Unsupervised and reinforcement learning	No need for labeling, autonomous operations	Complexity	Massive scale communications, eHealth, holographic telepresence, industry 4.0, unmanned mobility
Knowledge sharing	Speed up learning in new scenarios	Need to design novel sharing mechanisms	Massive scale communications, smart city, unmanned mobility

molecular absorption, as shown in Fig. 3. However, it is possible to avoid this loss by choosing deployments in frequency bands not severely affected by molecular absorption, with contiguous chunks of up to 200 GHz of free spectrum [10].

- **VLC** have been proposed to complement RF communications by piggybacking on the wide adoption of Light Emitting Diode (LED) luminaries. These devices can indeed quickly switch between different light intensities to modulate a signal which can be transmitted to a proper receiver [4]. The research on VLC is more mature than that on terahertz communications, also thanks to a lower cost of experimental platforms. 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. 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), thus can be mostly used indoors [4]. 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 in Sec. II, is a use case that has not been properly addressed by 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.

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

- **Integration of full-duplex capabilities in the communication stack.** With full-duplex communications, the transceiver in base stations and User Equipments (UEs) will be capable of receiving a signal while also transmitting, thanks to self-interference-suppression circuits [12]. Practical full-duplex deployments have been made feasible by breakthrough in the development of the aforementioned circuits only recently, thus have never been included into cellular network standards. These technology advancements can enable continuous downlink transmission with uplink acknowledgments or control messages (or vice versa), to increase the multiplexing capabilities and the overall system throughput without using additional bandwidth. Nonetheless, 6G networks will need careful planning for the allowed full-duplex procedures and deployments, to avoid interference, and novel resource scheduler designs [12].
- **Novel channel estimation techniques (e.g., out-of-band estimation and compressed sensing).** The channel estimation for Initial Access (IA) and beam tracking will be a key component of ultra-high frequencies communications in a cellular context, as for mmWaves. However, it is

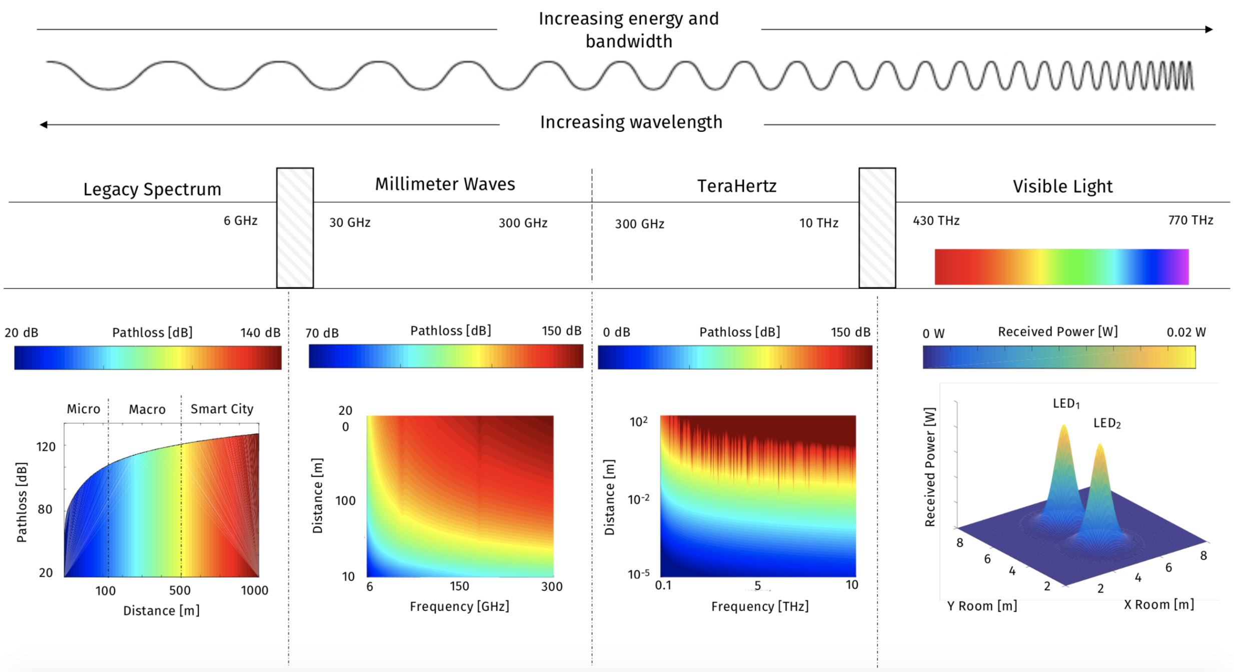

Fig. 3: Pathloss for sub-6 GHz, mmWave and terahertz bands, and received power for VLC. Notice that the limits of the axis and the legends are different in each frequency band, to better illustrate the differences and the possible scenarios in which each band could be exploited. The sub-6 GHz and mmWave pathloss is computed using 3GPP models and considers both Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions, while LOS-only is considered for terahertz (with the model from [10]) and VLC (using the model described in [11]).

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. Recently, out-of-band estimation (e.g., for the angular direction of arrival of the signal) has been proposed to improve the reactiveness of beam management schemes, by exploiting the omnidirectional propagation of sub-6 GHz signals and mapping the channel estimation to mmWave frequencies [13]. 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 [14], 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 (i) improve control operations, which can rely on context information to control beamforming patterns, reduce interference, predict handovers; and (ii) offer innovative user services, e.g., for vehicular and eHealth applications.

B. *Innovative Network Architectures*

The disruption brought by the communication technologies described in Sec. III-A 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 create constraints 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 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 architectural paradigms:

- **Cell-less architecture and tight integration of multiple frequencies and communication technologies.** 6G will break the current boundaries of cells, with UEs connected to the network as a whole and not to a single cell. This can be achieved, for example, through multi connectivity techniques, and the support for different and heterogeneous radios in the devices. The cell-less network procedures will guarantee a seamless mobility support, without overhead due to handovers (which might be frequent when considering systems at terahertz frequencies), and will provide QoS guarantees even in challenging mobility scenarios such as vehicular ones. The overcoming of the cell concept will also enable a tight integration of the different 6G communication technologies. The users will be able to seamlessly transition among different heterogeneous links (e.g., sub-6 GHz, mmWave, terahertz or VLC) without manual interventions or configurations in the device, which will automatically select the best available communication technology. Finally, according to the specific use case, the UE may also concurrently use different network interfaces to exploit their complementary characteristics, e.g., the sub-6 GHz layer for control, and terahertz link for the data plane.
- **3D network architecture.** Traditionally, networks have been designed to provide connectivity for an almost bi-

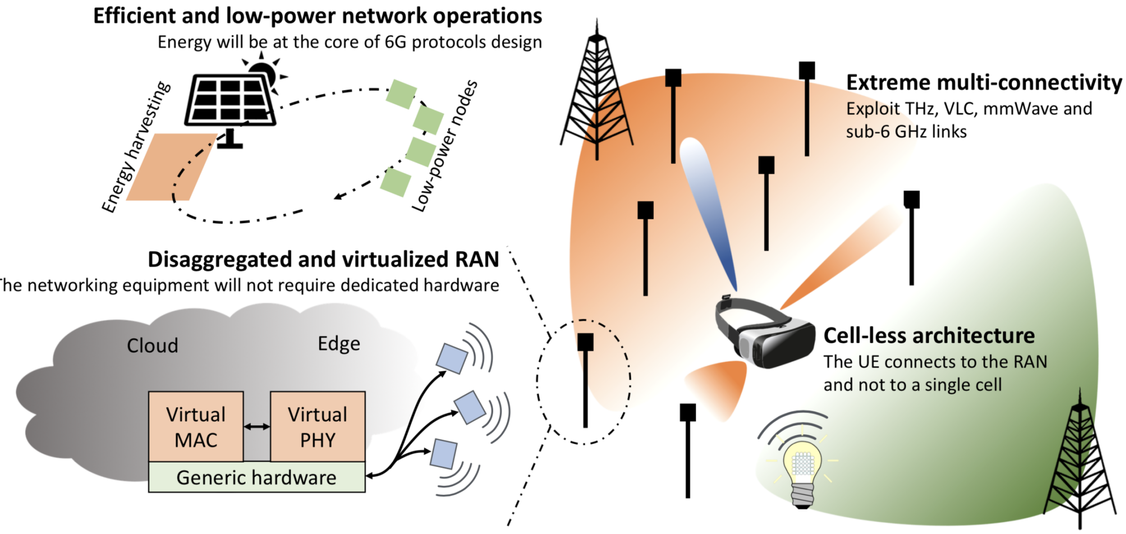

Fig. 4: Architectural innovations introduced in 6G networks.

dimensional space, i.e., 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 (3D) 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, e.g., in rural areas or during events, avoiding the operational and management costs of always-on, fixed infrastructures.

- **Disaggregation and virtualization of the networking equipment: from the physical layer to NFV.** Networks have recently started to transition towards the disaggregation of once-monolithic networking equipments: for example, 5G networks base stations can be deployed with distributed units with the lower layer of the protocol stack, and centralized units in data centers at the edge. Following this direction, 6G networks will adopt an even more disruptive architecture, where the units deployed on the ground will contain just the physical antennas and the lowest amount of processing units possible. Moreover, virtualization will be brought to the extreme, thanks to the advances in the capabilities of general purpose processors: 6G will virtualize additional components, such as those related to the MAC and PHY layers, which currently require dedicated hardware implementations. The virtualization will decrease the costs of networking equipment, making a massively dense deployment economically feasible.
- **Advanced access-backhaul integration.** The massive data rates provided by the new 6G access technologies will require an adequate growth of the backhaul capacity. Moreover, terahertz and VLC deployments will call for a massive increase in the density of access points, which should be provided with backhaul connectivity to their neighbors and the core network. However, the huge capacity of 6G technologies can be exploited for self-backhauling solutions, in which the radios in the base stations provide both access and backhaul services. While a similar option is already being considered for 5G, the scale of 6G deployments will introduce 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.
- **Energy-harvesting strategies for low-power consumption network operations.** 6G devices will be deployed in a pervasive manner to satisfy the future connectivity requirements. User terminals and networking equipment will need to be powered with energy sources and, given the scale expected in 6G networks, it is necessary to design the system to be more efficient and less energy consuming with respect to current networks. This means that both the circuitry and the communication stack will be 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 which are rarely used.

C. Integrating Intelligence in the Network

The complexity of 6G communication technologies and network deployments will probably prevent closed-form and/or manual optimizations. While the application of intelligent techniques in cellular networks is already being discussed in the 5G domain, we expect 6G deployments to be much denser (i.e., in terms of number of access points and users), heterogeneous (in terms of integration of different technologies), and with stricter requirements in terms of performance with respect to 5G. Therefore, the intelligence will play a more prominent role in the network, going beyond classification and prediction tasks which 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, in 6G systems there will be mechanisms such as:

- **Unsupervised and reinforcement learning techniques for real-time network decisions.** The application of unsupervised and reinforcement learning in networks is still in its infancy, but is promising in the context of complex 6G networks. The amount of data generated will indeed be massive, thus 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 truly operate in an autonomous fashion.
- **Inter-user inter-operator knowledge sharing.** Spectrum and infrastructure sharing has already been proven to be beneficial in cellular networks, to maximize the multiplexing capabilities. In an autonomous and machine-learning driven network domain, operators and users may also be interested in sharing learned 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 scenarios which may emerge during the operations of the network.

IV. Conclusions

In this paper, we presented an overview of the applications and the technologies that will characterize 6G networks. Table I provides a summary of the main challenges and potentials of each enabling technology, and relates each of them with the use cases that will exploit it. 6G networks will adopt new spectrum bands, combining advancements throughout the whole network stack, from circuit and antenna design to network architectures, protocols and artificial intelligence. While most of the technologies described in this paper are not market-ready, they represent promising possible enablers for the digital use cases of the 2030 society, including massive scale connectivity, truly indoor coverage, eHealth, robotics and unmanned applications.

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