6G: A Comprehensive Survey on Technologies, Applications, Challenges, and Research Problems

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6G: A comprehensive survey on technologies, applications, challenges, and research problems

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Abstract

The inherent limitations of the network keep on going to be revealed with the continuous deployment of cellular networks. The next generation 6G is motivated by these drawbacks to properly integrate important rate-hungry applications such as extended reality, wireless brain-computer interactions, autonomous vehicles, and so on. Also, to support significant applications, 6G will handle large amounts of data transmission in smart cities with much lower latency. It combines many state-of-the-art trends and technology to provide higher data rates for ultra-reliable and low latency communications. By outlining the system requirements, potential trends, technologies, services, applications, and research progress, this article comprehensively conceptualized the 6G cellular system. Open research issues and current research groups in their field of research are summarized to provide readers with the technology road-map and the potential challenges to consider in their 6G research.

1 | INTRODUCTION

The need for higher rates is the primary driver for the wireless network evolution. It is expected to mandate a continuous 1000x increase of the network capacity based on the continuous demand. The reason behind this tremendous need for higher rates is the emergence of the Internet of Things (IoT) in almost all industries to form industry 4.0. Millions of people and billions of machines will be connected to contribute to a revolutionary shift from rate-centric enhanced mobile broadband (eMBB) services to ultra-reliable, low latency communications (URLLC). However, one of the fifth-generation key features (5G) is enabling IoT and industry 4.0. Its initial premise of 5G has proved the right carrier of IoT services, but it still requires a lot of development to cope with the significant number of networks. No one can argue that 5G is an evolutionary generation for connecting, supporting IoT networks, and providing new services (ie, supporting eMBB services), yet it is still questionable whether it will deliver smart cities and smart utility services. It is still likely that 5G, in the beginning, will use sub-6 GHz for supporting mobility, although the fact of supporting fixed-access at millimeter-wave (mmWave) frequencies.

There is no doubt that 5G has been evolutionary in supporting rate-hungry eMBB services, working on high-frequency millimeter-wave (mmWave), and enabling heterogeneous IoT services. However, the unprecedented growth of new IoT services is ongoing to consider a broad range of applications, such as extended reality (XR) services, telemedicine, haptics, drones, brain-computer interfaces, and connected autonomous systems. These applications might not be fully compatible by the 5G as it aims to support short-packet, and sense-URLLC services. It requires a simultaneous delivery of high reliability, low latency, high data rates, and end-to-end design systems (in communication, control, and computing functionalities) in heterogeneous devices during uplink and downlink transfer. Accordingly, new challenges must be addressed to support several applications, such as characterizing the rate-reliability-latency trade-offs, the requirements to govern their performance, exploiting frequencies beyond sub-6GHz, self-sustaining of the operating frequencies, and intelligent orchestration system to handle the communication-computing control-localization-sensing resources for a specific IoT application/scenario.[1]

Therefore, to overcome these challenges, the sixth generation (6G) cellular network aims to inherently tailor the performance requirements to each IoT application/scenario with an adequate technological trend especially 6G is meant to improve the thing-to-thing communication.[2] The 6G is going to bring this revolution to connect (enable) everything worldwide using extreme communication techniques.[3] A convergence of the state-of-the-art technologies that is been used in previous cellular systems (eg, small-cell densification, higher rates, and massive antenna devices) will become the key attractions of 6G. Other new trends (eg, smart wearable devices, implants, XR systems, haptics, flying vehicles, etc.) have not been used in telecommunications to date, and are expected to be used in the 6G. Moreover, artificial intelligence (AI) algorithms (eg, network monitoring, business decisions driven by data, preventive maintenance, detection of fraud, etc.) and security systems (eg, blockchain for data validation) are also paramount to be realized in the 6G.[4,5]

Mobile potential, smart cities, wearable devices, autonomous vehicles, seamless virtual and augmented reality, AI, the IoT, and much more are far from being developed. It is only by looking forward to 5G and 6G that we get a preview of what might be feasible in the next 10 to 50 years. In addition, 6G is still estimated to be at least a decade away, likely to form inexpensive, fast internet for the entire world, with wireless speeds of up to 10 Gbps, and the ability to tap satellite communication networks.Many research centers are currently working on 6G and their trends and applications such as South Korea, Finland, China, and the United States (see Table 1). The Research group in Finland is considered the research flagship so far, and they consider the following 6G features; localization and sensing, trust, security and privacy challenges, and edge intelligence. China and Japan have claimed that they are working on 6G research groups, yet no outcomes have been published from their work. Moreover, a few published papers have involved the development of 6G vision, trends, technologies and applications.[1,6-9] In References 10 and 11, the authors discussed the significant

TABLE 1 Research initiatives into 6G communications

Country	Research initiatives	Research areas
Finland (2018)	It is coordinated by the University of Oulu.	• Terahertz spectrum. • AI applications. • Localization and sensing.
US (2019)	• The Federal Communications Commission with IEEE future networks under name “Enabling 5G and beyond.” • ITU-T Study Group no 13 for Network in 2030.	• Terahertz spectrum (95 GHz and 3 THz). • Reviewing service requirements. • Edge intelligence.
EU (2019)	• Terranova project. • An EU-Japan project under Horizon 2020 funding, called “Networking Research beyond 5G.”	• Terahertz spectrum (with 400 Gbit per second) and (100 to 450 GHz)
South Korea (2019)	• LG Electronics in collaboration with the Korea Advanced Institute of Science and Technology (AIST). In addition with a signed coloration agreement with the University of Oulu. • Samsung Electronics and SK Telecom work together on developing technologies and business models. Also, SK Telecom has signed agreements with Nokia firm in Finland and Ericsson in Sweden to conceptualize 6G network development.	• 6G applications. • 6G vision and key features. • Review of business models.
China (2019)	Two working groups to carry out the 6G research activities by orders from the ministry of science and technology; One with the government, and the second one with is made up of 37 universities, research institutes and companies.	Conceptualizing 6G.
China (2019)	• Japan invested US$2 billion to support industry research. • NTT and Intel have decided to form a partnership to work together.	Conceptualizing 6G.

achievements and challenges of 1G through 5G. They identified the essential requirements that could not be met by 5G, such as latency, capacity, energy, and network security. Moreover, they suggested several promising recent approaches to address the growing demands of various sectors, such as optical free-space communications, mm-Waves, multi-domain joint transmission, wireless charging and energy harvesting, and machine learning (ML). These works review the vision, trend, application, but it does not include any feedback on the progressive work with the research centers, and the applications are not investigated in detail. Therefore, the main contribution of this article is a detailed view of 6G systems, including the description of infrastructure specifications for leaps from current networks to 6G systems and recommendations for implementations, innovations, and performance indicators. The applications are evaluated, and the potential challenges are highlighted. The reader will be able to grasp the upcoming applications and their challenges as a research road-map.

This article is organized as follows; Section 2 summarizes the previous and current cellular networks with the need for the 6G. Section 3 answers the challenges mentioned through the vision and key features of the network. Section 4 reviews and proposes the applications and services that are expected to be deployed by 6G cellular networks. Section 5 reviews the on-going research activities and unanswered problems. Finally, Section 6 concludes the work.

2 | CURRENT CELLULAR NETWORKS

The 5G of mobile wireless networks have already been deployed in several countries. New wireless cellular communication has taken place every ten years since 1980, since all generations were released in 1981, 1992, 2001, 2011, and 2020. Throughout the last decade, the telecommunications industry has witnessed enormous development, leading to thriving data-hungry applications either in multimedia, online gaming, video streaming, and so on. The booming of mobile internet technology and IoT are enabling new services such as mobile shopping and payment, smart home/cities/industry, mobile gaming, and other user-defined services and IoT.[9,12]

The standardization of 5G has been completed, and the system is expected to be deployed around the world in a few years. The coverage map of the 5G commercial/trials testing/research developments are evaluated (see Figure 1). Approximately 85 cities in South Korea with 86 000 supported base stations to 5G in April 2019 are deployed with substantial 5G technology to support this need. Six out of these 85 cities have 85% of the located base-stations in South Korea, including Seoul, Busan, and Daegu, where a distributed system with a 3.5 GHz (sub-6) spectrum to support data rate 193 to 430 Mbit/s.[13] It is expected that 65% of the world's population will get access to 5G technology by the end of 2025.[14] A variety of new services in 5G cellular networks have proposed to involve enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (uRLLC), and massive machine-type communications (mMTC). The detailed information about the 5G vision, core and requirements is explained in References 15-17. With the on-going movement of smartening things at households, cities, or utilities, the magnitude of connected things and wireless data volume is expected to

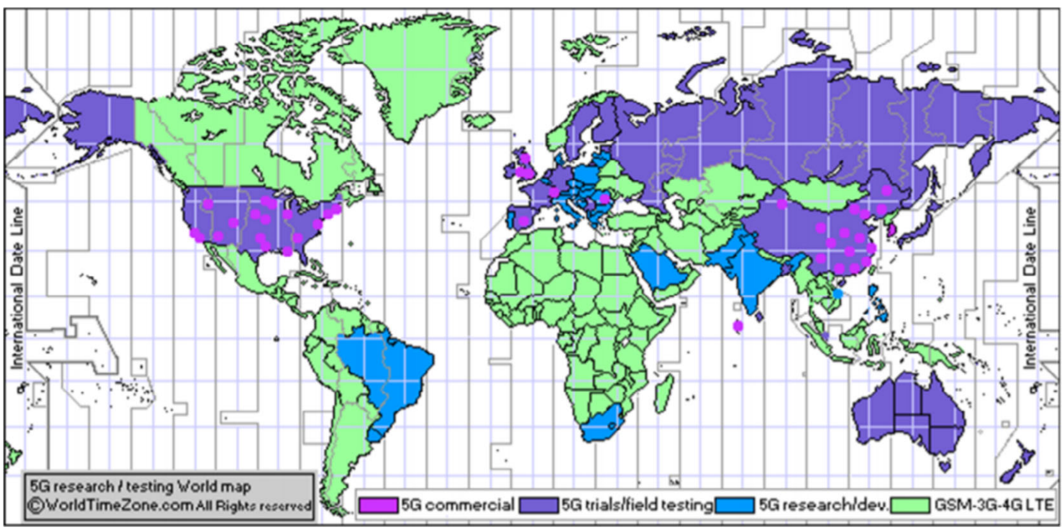

FIGURE 1 5G coverage map in December 2019[35]

increase tremendously. The development of data-hungry apps (ie, virtual reality gaming) has been improved through 5G technologies. However, some other applications (ie, sending holographic videos) still require a different spectrum bandwidth that is still unavailable in mmWave spectrum.[18] Therefore, using a broader frequency spectrum bandwidth has become mandatory, and this can be achieved by using terahertz (THz) and their sub-bands.

The recent increase of diverse mobile applications supported by artificial intelligence (AI) and edge computing algorithms is stimulating the crucial discussions on the future evolution of wireless communications.[4] Accordingly, industry and academia have been motivated to make a vision and conceptualize the next generation of the cellular system (6G) using the mentioned technologies and support the new requirements in the 2030s (see Figure 2).[9] Hence, the 6G cellular systems are expected to respond to these challenges by providing an extensive coverage to support the unconventional technologies that need extremely bandwidth (THz waves) and processing requirements either in the operational and environmental aspects.

ML, AI, and deep-learning and data science with data analytic and data mining will be the dominant technologies of the future 6G. These technologies are expected to make an impact in the physical, medium access control, networks, and applications layers.[9,19,20] First, prediction of the channel coding for larger number of bits, robust synchronization to support 6G requirements, mobile positioning for non-line-of-sight (NLoS) multi-paths, non-linear and non-stationary channel estimation, and adaptive and real-time massive MIMO beam-forming are the key ML applications in the physical layer.[21] In addition, many optimization problems in the physical layer can be realized, such as maximizing throughput by the optimal power control, multi-user spectrum optimization in multicarrier systems, optimization of spectrum sensing for cognitive radios, and optimal beam-forming formulation as a sum rate maximization problem by means of total power.[21] Second, predictive resource allocation, predictive power management, and asymmetric traffic accommodation are the core ML applications in the medium access control layer.[21] Third, securing the data during the transmission is the key application in the networks layer. Fourth, network performance management automation, aided unmanned aerial vehicles (UAVs) control, and opportunistic data transfer networks in vehicular are the core applications in the application layer.[21] However, there are many applications across most of the layers in the IoT devices and telecommunication networks, yet most of them are not yet confirmed to be potential applications in the 6G.

A comparative study between 5G and 6G is examined from many factors including the required specifications and systems capabilities (see Table 2). In comparison with the 5G, the 6G promised to deliver higher data rate in terabits, lower delay, higher degrees of reliability and sustainability, and provide better mobility. In a brief, the 6G can provide better data rate and mobility, support more device with less latency, and higher reliability. These improvements are realized to support the tremendous increase of connected devices and enable the rate-hungry applications such as extended reality, wireless brain-computer interactions, autonomous vehicles, and so on.

With the fast movement of the virtualization in telecommunication applications, many works introduced a virtualization network named virtualized-radio access network (V-RAN) or Fog-RAN (F-RAN) on the cloud-radio access networks (C-RAN) architecture.[22] The C-RAN is a centralized processing, collaborative radio, and a real-time cloud-based RAN. It allows many RRHs to connect to the centralized BBU pool, and any BBU can talk with any other without the BBU pool with very high bandwidth (>10Gbit/s) and low latency (<10 μm).[23] The V-RAN facilitates edge devices to carry a substantial amount of computation.[24-26] This movement continues to exploit new networks to realize open-radio-access network (O-RAN). This system replaces the legacy between the base-band unit (BBU) and the remote radio head (RRH), and it also supports different vendors.

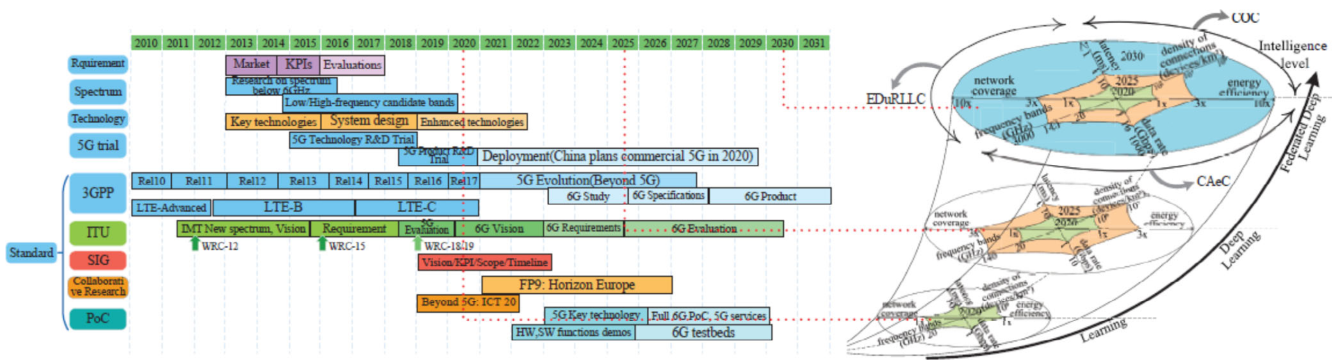

FIGURE 2 Timeline of 6G development networks[9]

TABLE 2 Requirements of 5G versus 6G

	5G	6G
Release year	2020	2030
Spectrum	3-300 GHz	73-140 GHz and 1-10 THz
BW	0.25-1 GHz	up to 3 THz
Data rate	1-20 Gbps	>1 Tbps
Spectral efficiency	30 bps/Hz	100 bps/Hz
Mobility	up to 500 km/h	up to 1000 km/h
End-to-end delay	5 ms	<1ms
Radio-only delay requirement	100 ns	10 ns
Processing delay	100 ns	10 ns
End-to-end reliability	99.999%	99.99999%
Connected devices	Smart phones, sensors, and drones	Smart phones, implants sensors, DLT devices, CRAS, CR and BCI equipment
Application types	eMBB, URLLC, and mMTC	MBRLLC, mURLLC, HCS, and MPS

Finally, many multi-access techniques have been introduced, such as delta-orthogonal multiple access (D-OMA), sparse code multiple access (SCMA), and filter bank multi-carrier (FBMC) to achieve massive access in 6G. The SCMA maximizes the total sum rate in C-RAN using SISO with a low complexity algorithm considering the QoS of each user, user association, and power constraints.[27,28] On the other hand, the D-OMA method relies on the idea of distributed large coordinated multi-point (CoMP) to enable the transmission of non-orthogonal multiple access (NOMA) using partially overlapping sub-bands for NOMA clusters.[29-31] The FBMC systems have recently attracted much attention as an alternative to conventional OFDM systems. Due to the use of the pulse-shaping filter, the FBMC has lower spectral side-lobes than conventional OFDM systems, which means that FBMC has asynchronous transmission abilities. There are three types of FBMC systems including filtered multi-tone-based FBMC (FMT/FBMC), cosine modulated multi-tone-based FBMC (CMT/FBMC), and offset quadrature amplitude modulation-based FBMC (OQAM/FBMC).[32-34]

3 | SYSTEM REQUIREMENTS, VISION, AND KEY FEATURES

The 6G architecture is proposed for the next generation of cellular networks (see Figure 3). This architecture will enable many processes such as securing the networks, attaining flexible networking, and enabling intelligent resource management. Considering the 6G security, many security and privacy issues have been raised to be tackled using potential technologies.[37] These security and privacy issues involve access control, malicious behaviour, encryption of data, and data communication, and the details of these issues and mitigation techniques are discussed (see Table 3). However, these issues are very crucial to maintain the proper security and privacy, but the research groups did not consider most of them in the 6G requirements, and some of them are expected to be embedded in the following system requirements.

- *More data rate, spectrum, and reliability:* It is expected that the new applications for 6G might require higher data rates than 5G. In order to cope with these applications (such as XR and BCI), 6G should provide modern technologies that can increase the data rate by 1000x in an attempt to advance a target of 1 Terabit/sec. This motivates the researcher to investigate using other frequencies beyond 6GHz further.
- *Spectral and energy efficiency:* 6G cellular network is expected to connect the applications on ground and aerial users and shall incorporate them with flying vehicles. This movement from spatial (aerial) to volumetric spectrum usage has changed the definition of bandwidth. Accordingly, 6G cellular systems have to maintain high spectral and energy efficiency (SEE) concerning the volumetric unit (bps/Hz/m3/joules).
- *Incorporation of smart surfaces with environments:* Former cellular networks used to develop various sizes and applications of base stations. 6G might have a different revolution toward the architecture by using smart, intelligent surfaces

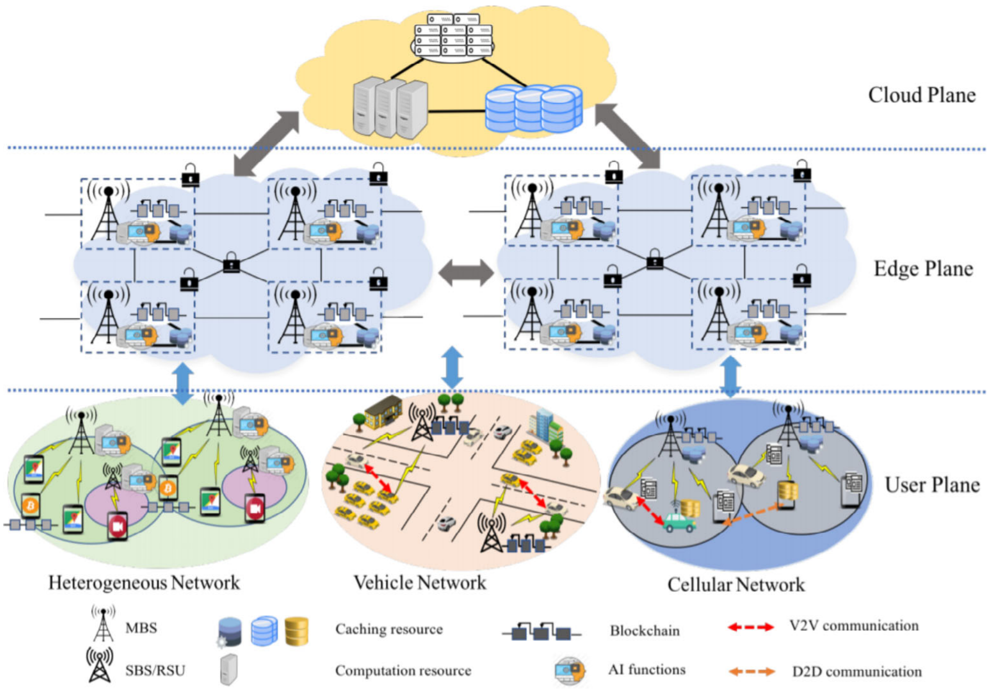

FIGURE 3 The secure and intelligent architecture of 6G[36]

TABLE 3 Key security and privacy issues in 6G

Issue	Solution	References
Unauthorized access control	Fine-tuned control processes using ML	38
	An improved access protocol using blockchain	39
	using unsupervised method in the authentication process to assure the genuinity of the authentication	40
Malicious Behaviour	Detect network anomalies and attain warnings using ML	5
	Identifying a disruption of molecular communication or its processes	41
	Perform analysis on Back-scattered data for high frequencies with narrow beams to detect eavesdropping	42,43
Encryption of data	ML and quantum encryption schemes	20
	Mechanisms for protecting quantum encryption keys	20
	A new coding scheme that can improve the security of data transmission using molecular communication technologies	44
Data communication	An antenna design using ML that can be deployed in the PHY layer	45
	Different modes of quantum communication	46
	Using hashing power to validate transactions using Blockchain	47
	A secure protocol that can be used in the communication process using VLC technology	48

and environments as wireless networks to create smart radio environments as adopted by the e-wallpaper project by Berkeley.[49,50]

- *Network automation and monitoring:* The data analytics revolution is expected to launch in 6G and is expected to see tremendous growth by 2030. This revolution is expected to process data traffic and shift networks from centralized to distributed systems (could be part of blockchain). 6G networks periodically review infrastructure data (industry 4.0) to improve network functions and tailor new services.
- *Self-organizing networks (SON) and self-sustaining networks (SSN):* A few research groups expected that SON would be integrated into 5G, but it was not deployed due to the real world's need. In contrast, the need for SON and SSN to manage network operations, resources, and optimization with CRAS and DLT devices will be mandatory in the 6G cellular network. The shifting paradigm from manual/classical SON to SSN in a highly dynamic and complex environment

capable of maintaining key performance indicators (KPIs) is one of the requirements of 6G. SSN considers the adaptation of functions and the maintenance of their use of and management of resources through spectrum exploitation and energy harvesting.

- *Convergence of communications, computing, control, localization, and sensing (3CLS):* Previous cellular systems were used to integrate communication, computing, control, and localization to provide wireless technology. The 6G intends to provide more essential services for some applications (eg, XR, BCI, CRAS, DLT, etc.). Moreover, 6G is planned to present a 3D mapping of the wireless environment for multiple frequencies.
- *More of wearable devices:* Smartphones used to be central around 4G and 5G, but wearable devices have been increasing recently, and new functions are gradually integrating into the systems. The XR and BCI applications fuel this movement to have a network that supports from wearable devices to smart body implants.

Other technologies have been recommended to be deployed in 6G by some research groups in order to address trends, network requirements, and applications.

1. *Beyond 6 GHz:* Higher data rates and SEE have motivated research groups to explore higher spectrum bands. This includes further exploration and development of the mmWave technologies extended to the terahertz (THz) band. This was the backbone of the 6G, making it a priority for most research groups. With the development of higher frequencies in the THz band, the base-stations of 6G are expected to shrink to tiny cells used mostly for densification.
2. *Transceivers with integrated frequency bands:* The urban growth of small cells may not meet the 6G requirement. Therefore, the integrated system allows multiple frequency bands (microwave/mmWave/THz) to leverage multiple local and wide-range services and functions. Cognitive Radio Networks (CRN) might be further integrated with this system that would allow some applications to access unallocated bands through the spectrum sensing process.[51,52]
3. *Smart radio environment using large intelligent surfaces (LISs):* Recent works proved that some intelligent surface incorporation with Massive MIMO might be integrated to provide higher data rates and better SEE in heterogeneous networks.[49,50] By exploiting this technique, new communication methods could be implemented, such as holographic radio frequency (RF) and holographic MIMO.
4. *Collective network and edge intelligence:* Recent breakthroughs in deep-learning, the rise of smart devices and IoT, and movement toward industry 4.0 have added much interest from the wireless community as the leading industry behind the other infrastructures/industries. Collective network intelligence is a terminology called to several artificial intelligence (AI) applications on 6G, such as creasing SSNs to maintain the sustainability of resources, functions, and control, and to provide multi-purpose 3CLS and energy services (MPS), and create 3D radio environment maps. This kind of intelligence is expected to be pushed at the edge devices (virtualization).[53,54]
5. *Integrated terrestrial, airborne, and satellite networks:* The incorporation of terrestrial, airborne, and satellite networks was one of the literature's ideas to enhance the connectivity of the network and cover blind spots and uncovered areas. Satellite networks with low orbit satellites (LEO) and CubeSats are essential for providing backhaul support and wide area coverage for drones and ground base stations for continuous connectivity.[1,55,56]
6. *Wireless energy transfer (WET) and harvesting (WEH):* Research groups in 6G cellular networks discuss the feasibility of applying the state-of-the-art results of energy harvesting systems to enable a wireless energy transfer (WET) base station for subscribed smart implants, sensors, and other devices based on the service.[57] Current research on this point also includes wireless energy harvesting (WEH) and backscatter technologies to allow transmitting energy to be harvested.
7. *Quantum computing and communication:* The security of high sensitivity information exchange has become a major topic in recent years. Encryption techniques require the shared use of strong keys. Due to the advancements in the field of quantum computing and possibility of real-time breaking of existing key-exchange algorithms, it is essential to explore new key-exchange techniques secure against advances in computing power. The major advantage of the quantum cryptographic system is that it allows the communicating users to detect any presence of third party this allows complete secrecy for the message being transferred in the system. The research in this era is still under-development, looking for an intersection point with 6G.
8. *Mobile edge computing (MEC):* Edge computing is an open platform that combines network, computing, storage capacity, mobility, and application capabilities at the edge of a network that is physically close to the data sources. MEC provides a value in which mobile operators can open their radio access network (RAN) to serve third-parties. This allows them to flexibly and rapidly deploy innovative solutions, applications and services to be provided to the

end-users and enterprise customers such as video analytics, video optimization, localization services, IoT, augmented reality, and data caching. The IoT represents one of the most significant disruptive technologies in various domains, such as smart cities, remote healthcare, intelligent transportation, industrial automation, autonomous driving, and disaster response. Billions of sensors and devices generate data and exchange information through IoT networks. Therefore, the MEC has three main shortcomings in the context of the IoT: (i) real-time demand for all things connected, (ii) data security and privacy, and (iii) large energy consumption. Such a method of data collection assists in many ways in enhancing customer service.

4 | DRIVING APPLICATIONS AND NEW SERVICES

Compatible applications with the 5G will indeed be central to the 6G even on a broader scale (supporting enormous large networks such as smart cities). Several emerging, fast-paced solutions are expecting to be deployed with the technologies mentioned earlier. The following applications are described:

1. *Multisensory XR applications*: Extended reality (XR) technologies include augmented reality (AR), mixed reality (MR), and virtual reality (VR). 6G expects to have a complete immersive ER experience that has not been realized in 5G due to the inability to maintain relatively low latency support. Mixed reality is not about overlaying any of the contents of the physical world as AR. However, it eliminates the distinctions between actual and virtual reality in which computer-generated objects will show something obscured in the physical environment. In order to cope with this type of application, there is indeed a popular format between technical requirements (eg, wireless, computing, storage) and physiological requirements (eg, human senses, cognition, and physiology). Perceptual criteria must be met through the design stage (computing, processing, etc.) to ensure quality-of-physical-experience (QoPE) - a new terminology.
2. *Connected robotics and autonomous systems (CRAS)*: The deployment of new CRAS applications was the primary factor behind the 6G movement. CRAS integrates flying-vehicles-delivery systems, autonomous cars, autonomous drone swarms, vehicle platoons, and autonomous robotics. These applications are not another short-packet up-link IoT service, as many applications are introduced in the 5G. However, they require stringent requirements in over latency and eMBB transmissions of high definition (HD) maps. Once again, the principle of QoPE applies to CRAS.
3. *Wireless brain-computer interactions (BCI)*: Along with the XR applications, smart body implants and BCI have become essential in 6G to support the literature's healthcare revolution. Current healthcare applications are limited to controlling biometric implant devices (eg, control prosthetic limbs or controlling something using brain implants). In 6G, wireless brain-computer interaction and interface with smart body implants will make a tremendous change in the healthcare system. It will introduce new use-cases that need 6G specifications for connectivity. The imminent use-cases are expected to enable brain-controlled movie input to fully-fledged multi brain-controlled cinema.[1,58] Also, some works compared BCI with body implants/biometric devices instead of smartphones, and it showed that individuals would gain control over their environment through gestures, empathic, and haptic. Also, use-case such as emotion-driven devices has been discussed to match a couple's mood. These applications require stringent requirements (such as high data-rates, ultra-low latency, and high reliability) as XR. However, BCI applications are much more sensitive than XR, and QoPE has to be assured.
4. *Blockchain and distributed ledger technologies (DLT)*: Blockchains and DLT devices are still under-developed in many industries, yet they are still immature. They have a lot of potentials in these next-generation distributed systems in terms of shifting from centralization to distribution systems for the sake of validating the data. They require high connectivity, a synergistic mix of URLLC and massive machine-type communications (mMTC) to maintain low-latency, reliable connectivity, and scalability.

As stated in the 6G trends, technologies, and applications, the 6G services will redefine those from the 5G by morphing the classic URLLC, eMBB, and mMTC and by introducing new services (see Table 4):

1. *Mobile broadband reliable low latency communication:* 6G applications could no longer be served by eMBB and URLLC, such as XR, BCI, and CRAS. This is because this technology demands high reliability, low latency, and extremely high data rates. As a result, a new service called mobile broadband reliable low-latency communication (MBRLLC) allows 6G networks to provide the required performance within the rate-reliability-latency space. Energy efficiency and limitation of the resources are two significant considerations for MBRLLC.

TABLE 4 6G summary services[1]

Service	Performance indicators	Example applications
MBRLLC	• Stringent rate-reliability-latency requirements. • Energy efficiency. • Rate-reliability-latency in mobile environments.	• XR/AR/VR. • Autonomous vehicular systems. • Autonomous drones. • Legacy eMBB and URLLC.
mURLLC	• Ultra high reliability. • Massive connectivity. • Massive reliability. • Scalable URLLC.	• Classical Internet of Things. • User tracking. • Blockchain and DLT. • Massive sensing. • Autonomous robotics.
HCS	QoPE capturing raw wireless metrics as well as human and physical factors.	• BCI. • Haptics. • Empathic communication. • Affective communication.
MPS	• Control stability. • Computing latency. • Localization accuracy. • Sensing and mapping accuracy. • Latency and reliability for communications. • Energy.	• CRAS. • Telemedicine. • Environmental mapping and imaging. • Some special cases of XR services.

2. *Network slicing:* Network slicing was proposed as a solution to support a range of service requirements. Network slicing produces various logical networks, each configured for a particular service, overlaid on shared physical infrastructure. The ITU-R proposed a slice for each of the 5G services, a URLLC slice, an eMBB slice, and an mMTC slice.[59] In order to further distinguish the requirements of different industries within the same slice, the 3GPP specifications suggested the inclusion of an additional field called the slice differentiator (SD) to extend the slice vertically.[60] Not all industries within the same slice can fit into the same protocol stack, so individual slices need to be broken down into more than one slice. Clustering services that may fit into the same protocol stack have not previously been discussed in the literature. This approach could reveal the ability of network slicing to support the complex requirements defined in 6G networks.
3. *Massive URLLC:* Smart factories were one of the applications in 5G, and using URLLC is intended to maintain reliability and latency during the up-linking of data. On the other hand, 6G must enhance the traditional URLLC and introduce a new dimension leading to a new massive URLLC (mURLLC) service that can meet 5G URLLC with legacy mMTC. The mURLLC expects to carry the reliability latency-scalability trade-off to the next level.
4. *Human-centric services (HCS):* The imminent form of 6G service focuses on enhancing human intractability, such as XR, BCI, and so on. However, QoPE needs to be guaranteed. It is, therefore, required to identify a new set of QoPE metrics to support these applications.
5. *Multi-purpose 3CLS and energy services:* 6G cellular networks plan to deliver 3CLS services and potentially provide wireless energy transfer (WET) services to smart devices. Some CRAS applications will require connectivity, including multi-purpose 3CLS and energy services (MPS). Designing MPS should consider a standard framework between up-link and down-link to meet the performance requirements for stability latency, energy transfer, localization, and procession.

Figure 4 outlines the applications, trends, and enabled technologies that will drive the evolution of 6G systems. Future 6G networks can benefit from the knowledge gained from multiple technologies and the solutions achieved by 5G. Improving network performance, integrating multiple techniques, and enhancing QoS are the key challenges of 6G technologies, offering a super-smart community with everything connected to the network.

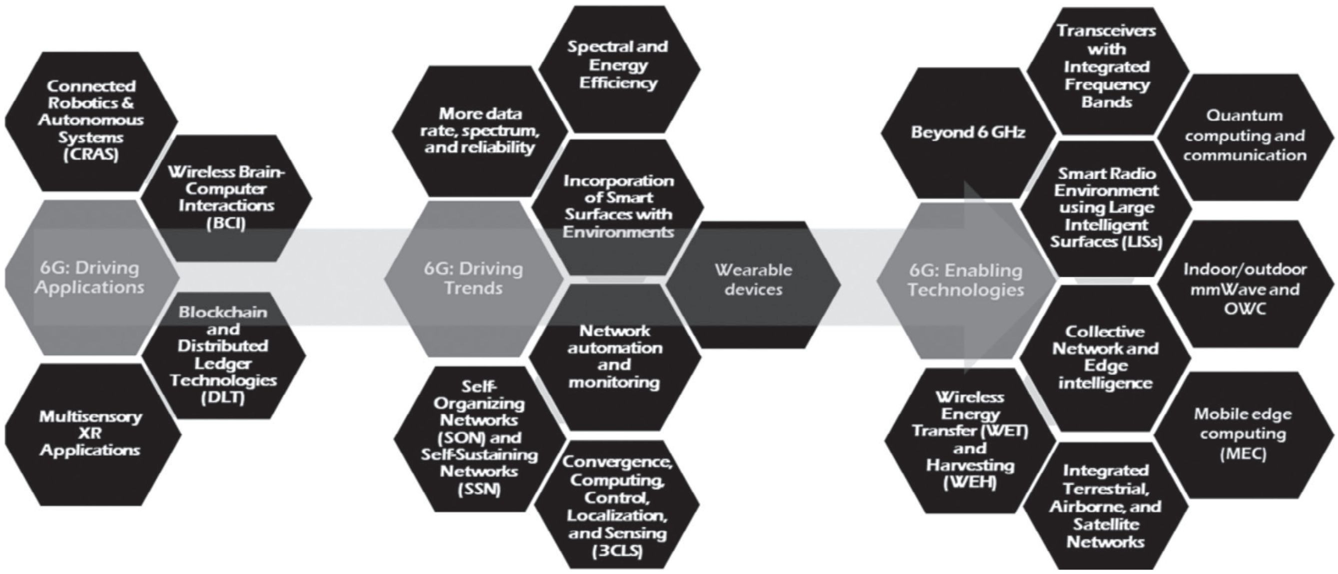

FIGURE 4 6G applications, trends, and technologies

5 | ONGOING RESEARCH AND OPEN PROBLEMS

This section focuses on the ongoing research areas and open research problems to the 6G trends, technologies, and applications.

1. *Integrated heterogeneous multiple frequency bands:* Exploiting THz with mmWave was the number one focus of many research groups, as it is the backbone of higher data rates. Supporting high mobility at mmWave is the current focus of mmWave research. The THz works focus on developing new transceivers and propagation models that can operate on such a high-frequency.[61] This research involves high-power, sensitivity, low noise levels. Another important research direction is deploying multiple spectra in the network to provide more flexibility in transmission. Bennis et al studied the co-existence of THz, mmWave, and microwave technologies at base stations.[62] A further research direction is integrating optical, visible light communication (VLC), molecular communication, and neuro-communication. In other words, a network that can thoroughly combine RF and optical signals.
2. *Resource allocation:* Allocating physical resources for the virtualized computing, storage, and communication resources in different network slices was a challenging problem in 5G systems that persist in 6G systems. A service orchestrator decides whether to execute service on an edge node, the cloud, or even the IoT device itself according to the service's QoS, the network state, and the available resources. Other factors considered for resource allocation are the overall energy consumption, resource utilization, and the priority of different requests in claiming the resources. Most works represented the resource allocation decision as a multi-objective optimization problem or a joint optimization problem. Optimization techniques suggested include greedy algorithms,[63] genetic algorithms, and graph theory-based algorithms.[64]
3. *Ultra low latency:* One of the main requirements of the 6G is to have ultra-low latency to support many applications (eg, XR, CRAN, BCI, etc.). Maintaining reliability between rate and latency is a key constraint in the development of ultra-low latency support architectures along with the provision of SEE. Kasgari and Saad have proposed a deep reinforcement learning system to develop the URLLC.[65] Bennis and Debbah reviewed the tail, risk, and scale of the architecture for enabling URLLC.[66]
4. *Decentralization networks:* Many works are considered focusing on decentralized rather than centralized ones, such as health care, electricity, water, and so on. This revolution comes with blockchain technology that can validate data through a decentralized network mode (without the need for the authorities to validate the data). Although many works addressed the implementation of blockchain in communications, the technology still under development, and the network might not be able to handle these huge amounts of computation may be required.

5. *Integration of terrestrial, airborne, and satellite:* 5G has been able to accommodate heterogeneous networks and diverse networking technologies (eg, Wi-Fi, D2D, etc.). Similarly, the integration of drones-base stations, terrestrial stations, and satellites has not been considered to ensure connectivity in places that do not have an infrastructure. Successful network planning that can be considered as 3D by the plan is essential. Bennis et al have shown the importance of having a 3D network instead of a 2D network and the corresponding degree of freedom.[55] Optimization of mobility management, routing, and 3D networking resources is expected to support the 6G vision.
6. *AI use-cases:* AI has been used in many telecommunications applications for 6G. In addition to data analytics applications in network monitoring, business decisions, fraud detection, preventive maintenance, SON and SSN, and so on, work on that application is also expected. In our previous work, we investigated potential applications that are compatible with 5G applications. In contrast, some other challenges might enable the use of AI in their problems, such as the use of deep reinforcement learning in the URLLC.[65]
7. *Emerging LIS with environment:* Emerging LISs in the environment to work as a smart radio environment is another open research direction. This research problem involves active frequency selection surfaces, metallic passive reflectors, passive/active reflectarrays, non-reconfigurable, and reconfigurable met surfaces.[49,50] Optimization of the passive reflectors and metasurfaces' system deployment is another open research problem, and AI can be used. The data rate, latency, reliability, coverage are fundamental elements in this analysis, as investigated by Hu et al.[50] One more research problem is improving the range and coverage of the tiny cells made from LIS.
8. *QoPE metrics:* Design of this performance metric that represents the consistency of the life of physical factors. This includes theoretical development at the beginning, based on mathematical expressions that can combine the quality of service (QoS), quality of experience (QoE), and human experiences. Bennis et al concluded that the development of this metric might well be based on a combination of other disciplines such as operations research (eg, multi-attribute utility theory) and AI.[1]
9. *3CLS:* The joint design of computation, communication, control, localization, sensing, and energy needs to be addressed in future research. There is a collaborative development in 5G between communication and control, but it requires to be extended to add the rest of the 3CLS functions. The interdependence between computing, communication, control, localization, sensing, energy, and mapping needs to be investigated since it has not yet been thoroughly reviewed.
10. *Dynamic multiple access and handover:* A new radical protocol is needed for the applications mentioned. Protocols that use AI for signaling, scheduling, and synchronization that can replace conventional 5G protocols. Another research direction is to find a new dynamic multiple access to dynamically adapt the multi-access technique (orthogonal or non-orthogonal, random or scheduled). Also, the simulation of modern transfer protocols is another direction of an investigation. Furthermore, new authentication and identification protocols will also be required to verify the new generation of wireless devices, including drones and implanted devices.
11. *Trust, security, and privacy:* Previous cellular networks focused on the core network metrics (eg, throughput, reliability, and latency) with little attention to security, secrecy, and privacy issues. In 5G networks, traditional encryption algorithms using Rivest Shamir-Adleman (RSA) public-key cryptography are used in 5G cellular networks to maintain transmission security and secrecy. On the other hand, with the development of big data and AI technologies, RSA has become insecure. Therefore, novel privacy-preserving mechanisms are still required. One more research problem is that with the blockchain work's progress, the need to have a data validation mechanism in each industry has become crucial. Hence, having a data validation mechanism through a smart contract is required.
12. *Potential health issues:* With the expected high data rates (in terabit/second), human safety and well-being could be affected by the propagation of such high frequency. The Federal Communications Commission (FCC) and the International Commission on Non-Ionizing Radiation Protection standards help avoid humans potential hazards. Also, careful consideration of the environment should be taken from the propagation of the THz radiation in terms of biological and molecular impact. Some works investigate that using electromotive force transmission could mitigate these health issues, but the research is still far away from being matured.[67]

6 | CONCLUSION

This article comprehensively conceptualized the 6G cellular system by outlining the system requirements, potential trends, technologies, applications, and research progress. The open research problems and the current research groups with their research field are summarized to provide readers with the roadmap of the technology and the potential challenges to consider in their research toward 6G.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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