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REVIEW

6G Mobile Communication Technology: Requirements, Targets, Applications, Challenges, Advantages, and Opportunities

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Abstract The sixth-generation (6G) technology of mobile networks will establish new standards to fulfill unreachable performance requirements by fifth-generation (5G) mobile networks. This is due to the high requirements for more intelligent network, ultra-lower latency, extreme network communication speed, and supporting massive number of various connected applications. In the long term, the convergence of various business developments with communication platforms, as initiated by 5G, will exaggerate and highlight areas where 5G's capabilities will fall short of performance requirements. Motivated by the development of applications in massive connections, future networks, developments, and technological advancements for mobile communications that go beyond fifth-generation (B5G) networks are being developed. In this context, highly immersive applications are demanded, such as three-dimensional (3D) communications, digital twins, or massive extended reality (XR)/virtual reality (VR) applications, which will need 6G capabilities to be realized at scale to be commercially feasible. Mainly, we anticipate that only the upcoming 6G networks will be capable of running extremely high-performance connectivity with massive numbers of connected devices, even under laborious scenarios such as extreme density, diverse mobility, and energetic environments. In this article, we look at the most recent trends and future emerging trends that are possible to operate 6G network. Paper aims to provide more inclusive and brief review about 6G mobile communication technology in one survey paper. Initially, a comprehensive overview of the 6G system is introduced in terms of visions, drivers, requirements, architecture, and usage

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scenarios required to enable 6G applications. After that, the opportunities and advantages of 6G mobile technology has been discussed. Further, the promising new techniques that enable 6G technology has been highlighted. This is followed by a potential discussion of challenges and research directions. This article is envisioned to serve as an informative guideline to stimulate interest and further studies for subsequent research and development of 6G networks. Paper will enable the readers to briefly figure out the key requirements, targets, that will be need and the applications, advantages, and opportunities that can be offered as well as the challenges that need to be addressed before the implementation of this new technology.

Contents

1. Introduction

Over the last three decades, mobile communication networks have undergone significant revolutionary development [1–3]. Several emerging applications and sectors have rapidly grown to include the internet of everything (IoE), virtual reality (VR), three-dimensional (3D) media, artificial intelligence (AI), machine-to-machine (M2M) communication, enhanced mobile broadband (eMBB), etc. The enormous potential of 5G has experienced radical changes, directing a massive volume of emerging scenarios. The 5G mobile network is already implemented in some parts of the world. Approximately 65 % of the world's population is expected to access the 5G network by the end of 2025 [1,4]. The continuous progress of the 5G mobile communication system is constantly revealing significant restrictions to this network. Its original principle is to empower the IoE. However, due to limited capacity, the 5G system is unable to achieve a fully intelligent and automated network that enables IoE as a service [5]. For instance, the next version of virtual augmented reality (VAR) requires Tbps-data rate and ultra-low latency, which cannot be met even with the new frequency bands of the 5G system. The increase in industrial automation and the transition from Industry 4.0 to Industry X.0 will further increase massive connectivity far beyond the specifications that 5G was originally planned for. The current network administration assessments must also be renovated. Increased connection density will further raise the demand for enhanced energy efficiency, which is not possible in 5G [6]. The rapid development of data-centric and automated systems may eventually overtake the capacity of 5G and existing mobile networks. The upcoming 5G network cannot fully meet the rapid progress and technical requirements of new technology.

5G will reach its limit by 2030, prompting the development of new paradigms to overcome the challenges in previous mobile network generations. The 6G mobile network is expected to attain high practical standards that meet the performance requirements of IoE, VR, 3D applications, AI, M2M communication, eMBB and their supplementary technological directions [7].

It is expected that the 6G network will provide a 100x increment in energy and volumetric spectral efficiency [22–24] compared to the 5G network. The 6G infrastructure will be extremely complicated due to massive connectivity. Global mobile data traffic is expected to increase by 55 % per year between 2020 and 2030 [10]. The anticipated traffic growth will generate 5,016 exabytes (EBs) of monthly data by 2030. This massive amount of data, with powerful processing and learning abilities, can be harnessed to control the network at different stages.

The research community is currently discussing the direction toward the sixth-generation (6G) and vision of 6G mobile networks under various known as B5G, 5G+, and 6G. Several research papers, such as [8–12], have been recently published that examine the vision and open challenges of the 6G network. The authors in [8] investigated different opportunities and the possible enabling technology for 6G mobile networks. The 6G mobile network vision was explained, and its requirements were examined based on development trend estimations of previous wireless communication networks (1G to 5G) in [9]. Ref. [10] introduced an overview of 5G network restrictions that prevent the achievement of high network performance requirements. Various innovative technologies were further discussed to meet the requirements for 6G mobile network. The demand for B5G will rise in order to achieve a further growth (up to 100x) for individual and 50x for downlink data rates. Ref. [11] highlighted the necessity for 6G by analyzing the gap between innovative ambitions and mature 5G networks. The authors also provided an overview of technology and future services based on a new mobile network infrastructure. The authors in [12] discovered several limitations of emerging 5G mobile networks and discussed the methods of enabling the 6G communication system to potentially overcome these limitations.

Ref. [13] claimed that 6G mobile networks must be human-centered. Therefore, security, confidentiality, and privacy are the main significant features. The methodical structure, key technology, and estimated challenges were identified to meet this fundamental vision. A survey on different machine learning (ML) technologies was subsequently conducted to include networking, communications, and security aspects of vehicular networks. Ref. [14] further presented a vision of the path towards a 6G smart vehicle network. The authors of [15] predicted several potential 6G opportunities, introducing a variety of technologies that will empower these opportunities. Viswanathan et al. [16] highlighted the widespread communication

Table 1 Summary of recent significant studies on 6G.

Ref.	Pubic. Year	Area of research	Major contributions and research directions
[29]	2020	Key issues and challenges	The future issues and challenges that 6G technology will face are discussed.
[30]	2020	Survey	The expected 6G emerging technologies are introduced, along with some difficult issues. Furthermore, the anticipated applications, as well as the requirements and potential technologies, are explained.
[31]	2020	Access and fronthaul/ backhaul networks	A survey of technologies for providing connectivity to rural areas is conducted. Furthermore, access/fronthaul and backhaul techniques are covered. Furthermore, the energy requirements and cost-effectiveness of the investigated technologies are examined.
[27]	2020	Edge computing	The evolution and convergence of 5G and iot technologies toward 6G networks are investigated.
	2020	Vision	Tries to argue that 6G must be human-centric, so security, secrecy, and privacy are important features. A systematic framework, required technologies, and challenges are outlined to support this vision.
[14]	2019	Vehicular	Discusses various ML technologies that are promising for vehicular network communication, network operation, and security, and envisions paths to an intelligent vehicular network, such as intelligent radio, network intelligence, and self-learning
[15]	2020	Use cases	Envisions a number of potential use case scenarios and key technological trends that are recognized as enablers for these 6G use cases
[16]	2020	Survey	New human–machine interfaces, ubiquitous computing, multi-sensory data fusion, and precise sensing and actuation are among the new themes. Then, with an emphasis on AI's potential, major technological transformations such as new spectrum, new architecture, and new security arcs were presented.
[17]	2020	Survey	A thorough discussion of 6G based on a review of SG developments, covering visions, requirements, technology trends, and challenges, attempts to highlight the approaches to addressing the challenges of 6G communication system coverage, capacity, data rate, and mobility.
[12]	2020	Survey	A 6G vision in terms of applications, technological trends, service classes, and requirements, as well as the identification of specific enabling technologies and open research issues.
[32]	2020	Survey	A survey on 6G applications, requirements, challenges, and research directions was carried out. Several key technologies were briefly discussed., including AT, THz, blockchain, and wireless optical communications.
[10]	2020	Vision	This article expands on the 5G vision to more ambitious scenarios in the future, speculating on the visionary technologies that can provide the step developments required to enable 6G.
[33]	2020	Vision	This paper defines the vision, new application scenarios, and crucial performance requirements, as well as suggests a logical mobile network architecture.
[34]	2020	Survey	A brief overview of various 6G problems, such as core services, use cases, requirements, enabling technologies, architectures, typical use scenarios, challenges, and research directions.
[35]	2020	Survey	A thorough study of 6G visions, requirements, challenges, and open research issues, outlining seven disruptive technologies: millimeter wave (mmWave) communications, THz communications, optical wireless communications, programmable *meta*-surfaces, drone-based communications, back-scatter communications, and Tactile Internet.
[36]	2020	Channel	This article analyzes 6G wireless channel measurements and models across all frequency bands, application scenarios, and global coverage.
[37]	2020	VLC	The authors discuss the prospects and challenges of VLC in 6G, as well as its advancements in high-speed transmissions and recent research interests such as new materials and devices, advanced modulation, and underwater VLC.
[11,37,38]	2020	UAV	The paper focuses on the advantages of unmanned aerial vehicles (UAVs) in improving network coverage and capacity, and it proposes a network configuration based on tethered UAVs.
[39]	2021	Survey	A comprehensive study is presented that depicts the 6G system in terms of drivers, use cases, usage scenarios, requirements, key performance indicators (KPIs), architecture, and enabling technologies.
[40]	2021	Survey	A comprehensive survey of current 6G developments is extensively explored.
[41]	2021	Survey	By introducing requirements, features, critical technologies, challenges, and applications, this survey provides an in-depth understanding of 6G wireless communications.
[42]	2021	Survey	This study focused on convergent 6G communication, localization, and sensing systems, identifying key technological enablers, trying to discuss underlying challenges and future challenges, and suggesting possible solutions.
[43]	2021	Survey	This article discusses system requirements, potential trends, technologies, services, applications, and research advancements.

Table 1 (*continued*)

Ref.	Pubic. Year	Area of research	Major contributions and research directions
[44]	2022	Review	This paper presents an investigation into the crucial problems and challenges associated with the security, privacy, and trust issues of 6G networks.
[45]	2022	Survey	This paper conducts a related study in terms of the 6G network's vision, requirements, and expected application scenarios. It also describes the integration of intelligent architecture and space, air, ground, and sea networks, and it exposes and analyzes the most important potential key technologies required for the future 6G.
[46]	2022	Review	The vision, requirements, enabling technologies, and challenges of 6G mobile technology are discussed in this paper. In addition, it compares 5G and 6G services, key technologies, and enabling communication techniques.
This work		Survey	To supplement previous studies, this article comprehensively reviews the latest developments in 6G research and provides a broad discussion in terms of requirements, targets, usage scenarios, key performance indicators (KPIs), architecture, applications, challenges, and opportunities for enabling new technologies that 6G networks will bring into our lives

Table 2 Comparison of 6G with 4G and 5G mobile communication systems.

KPIs	4G	5G	6G
Peak data rate /device	1 Gbps	10 Gbps	1 Tbps
latency	100 ms	1 ms	0.1 ms
Max. spectral efficiency	15 bps/Hz	30 bps/Hz	100 bps/Hz
Energy efficiency	< 1000x relative to 5G	1000x relative to 4G	> 10x relative to 5G
Connection density	2000 devices / km^2	1millon devices /km^2	> 10millon devices/km^2
Coverage percent	< 70 %	80 %	> 99 %
Positioning precision	Meters precision (50 m)	Meters precision (20 m)	Centimeter precision
End-to-end reliability	99.9 %	99.999 %	99.9999 %
Receiver sensitivity	Around −100dBm	Around −120dBm	< −130dBm
Mobility support	350 km/h	500 km/h	≥1000 km/h
Satellite integration	No	No	Fully
AI	No	Partial	Fully
Autonomous vehicle	No	Partial	Fully
Extended Reality	No	Partial	Fully
Haptic Communication	No	Partial	Fully
THz communication	No	limited	Widely
Service level	Video	VR, AR	Tactile
Architecture	MIMO	Massive MIMO	Intelligent surface
Max. frequency	6 GHz	90 GHz	10 THz

demands and technology in the 6G era. Novel topics have been introduced to potentially shape 6G requirements. Ref. [17] provided an inclusive discussion covering visions, requirements, challenges, and rapid technology directions to simplify the methods needed to address coverage, capacity, mobility [2,18,19], and data rate challenges for 6G mobile systems. From the perspective of networking communication and computing, researchers identified potential challenges and possible study directions for developing ML technologies in the future 6G network [20]. Guo [21] highlighted the basic concepts of interpretable AI for 6G, including general and legal motivation factors, definition, the trade-off between interpretability and performance, interpretable methods, and an interpretable AI framework for future mobile communication systems.

To achieve all these requirements and future vision, the main factors of the generational jump beyond current mobile communication systems would be the combination of social necessities and technological revolutions that empower those necessities. When these factors are considered together, they make a strong argument regarding the next boundaries in wireless networks. The features of 6G mobile technology go beyond the intelligence, reliability, scalability, and security of ground mobile networks. They will empower satellite communication integration to form an ubiquitous mobile network, in line with the need to have a truly global wireless network presence [6]. Therefore, several key solutions have been investigated in terms of vision, specifications, requirements, and expected technology for 6G [5,12,25–27]. To meet the 6G targets, overcome the limitations of 5G, and support new challenges, mobile communication systems in 5G and beyond must be enhanced with new and sophisticated features. The 6G network will enhance the 5G system lag by introducing a novel set of technologies that include: a THz-band operating system, allocation-resources, ubiquitous AI, massive network automation, intelligent network environments, ambient backscatter communication, internet of space things (IoST),

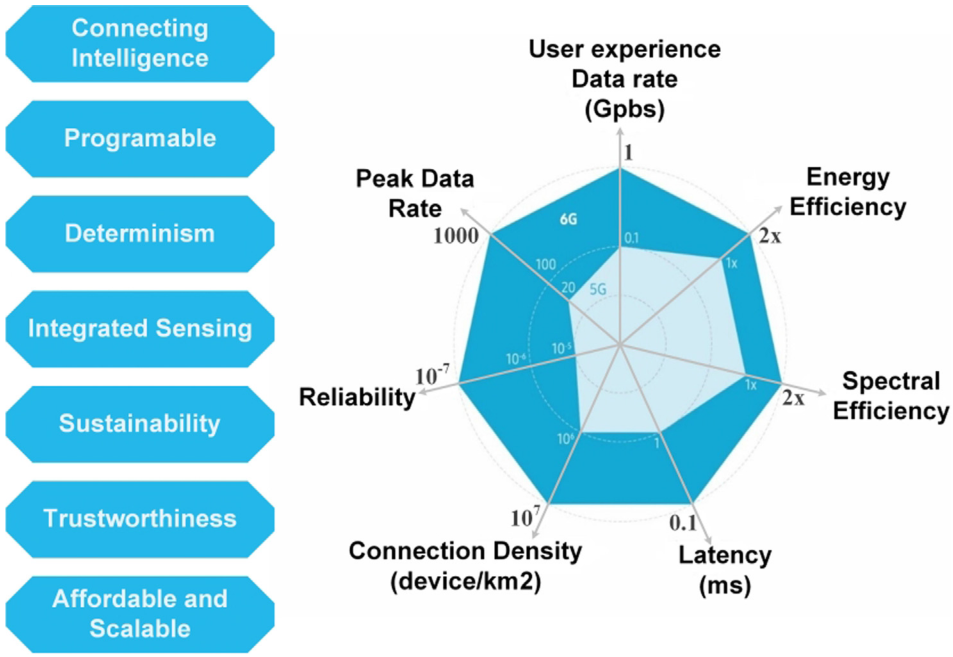

Fig. 1 Key enhancements of 6G technology.

massive MIMO cellular networks, and human-to-human (H2H) communication [6,28]. Three upcoming features are also expected to change future mobile networks, but they will not be mature enough for 6G. These features are quantum communications, the internet of nano things (IoNT), and the internet of bio nano things (IoBNT) [11,12]. A discussion of systems beyond 6G (such as IoNT, IoBNT, and quantum communications) is equally important yet absent from current publications. Table 1 illustrates latest research work that studies developments in various areas of 6G.

Despite the few studies that have been conducted to provide a thorough view, no previous study has comprehensively surveyed the most recent advances in 6G research. In order to supplement previous studies, this article comprehensively reviews the latest developments in 6G research and provides a broad view in terms of requirements, targets, applications, challenges, and opportunities for enabling new technologies that 6G networks will bring into our lives.

Consequently, the contributions of this article can be summarized as follows:

- **Exploring 6G technology:** This survey outlines the importance of a vision and trends for driving 6G, highlighting the key requirements. In addition, it clarifies three possible new usage scenarios for 6G, envisaging the 6G architecture and summarizing the ongoing and recent studies on 6G that focus on developing the 6G vision and technologies.
- **Discuss emerging applications:** Development of a variety of new opportunities that are predicted to thrive is briefly explained, with an emphasis on how these applications are enabled by future 6G network capabilities.
- **Discuss enabling technologies:** New expected enhancement technologies that will enable the 6G and meet the demands of emerging applications are thoroughly discussed.
- **Challenges and research directions:** Potential challenges and research questions that require solutions and research directions to achieve the 6G target are discussed and summarized.

The rest of this article is arranged as follows: Section 2 introduces an overview of 6G technology in terms of requirements, specifications, network architecture, usage scenarios, and current ongoing research activities regarding 6G technology. Section 3 presents general information on the advantages and opportunities brought by the new technology, including the application areas and usage, and their effects on our lives. Section 4 highlights the key technology expected to enable the 6G system. Section 5 discusses several possible requirements to effectively implement 6G mobile networks, further identifying the main challenges and future directions to accomplish the goals of 6G technology. Finally, Section 6 concludes this article.

2. 6G mobile technology

Mobile technology is where the user has "mobility". Although wireless communication provides several conveniences, it also includes numerous risks and problems. Since the early 1970 s, these problems have been resolved throughout different generations. 6G is now the current wireless communication technology in development, a gradual evolution from the initial 1G. 6G is the technology that will enable the 6G wireless communication system to become a reality. Wireless generations are released approximately 10 years apart. Assuming that this trend continues, 6G is expected to enter our lives around 2030. The general characteristics of all generations are discussed in order to clearly see the progress between generations since the 1G.

Frequency division multiple access (FDMA) multiplexing with a speed of 2 Kbps was initially used for the 1G [47]. It

Table 3 Features comparison of 4G, 5G, and 6G mobile communication systems.

	4G	5G	6G
Usage Scenarios	Mobile Broadband (MBB)	eMBB, uRLLC, mMTC, FeMBB, ERLLC umMTC	FeMBB, muRLLC, umMTC, eRLLC, MBRLLC, uHDD, uHEE, uHS
Applications	• High-Definition Videos • Voice • Mobile TV • Mobile Internet • Mobile Pay	• VR/AR/360° Videos • UHD Videos • V2X • IoT • Smart City/Factory/Home • Telemedicine • Wearable Devices	• Holographic Verticals and Society • Tactile/Haptic Internet • Full-Sensory Digital Sensing and Reality • Fully Automated Driving • Industrial Internet • Space Travel • Deep-Sea Sightseeing • Internet of Bio-Nano-Things
Network	Flat and All-IP	• Cloudization • Softwarization • Virtualization • Slicing	• Intelligentization • Cloudization • Softwarization • Virtualization • Slicing
Characteristics	People	Connection (People and Things)	Interaction (People and World)
Technologies	• OFDM • MIMO • Turbo Code • Carrier Aggregation • HetNet • ICIC • D2D Communications • Unlicensed Spectrum	• mm-wave Communications • Massive MIMO • LDPC and Polar Codes • Flexible Frame Structure • Ultra dense Networks • NOMA • Cloud/Fog/Edge Computing • SDN/NFV/Network Slicing	• THz Communications • SM-MIMO • LIS and HBF • OAM Multiplexing • Laser and VLC • Blockchain-Based Spectrum Sharing • Quantum Communications and Computing • AI/ML

Table 4 The envisioned variances between 5G and 6G network architecture.

Parameters	5G	6G
Type of service	Point to point QoS transport	Point-to-multipoint transport, including configurable logical network overlay topologies with managed quality properties and net-app awareness, with compute services, sync services, AI services
Type of resources	Communication	Communication + compute + sensing
Architecture scope	Radio access network (RAN) + Core network (CN)	Terminal + RAN + CN
Cloud-native	Only control plane (CP) in 5G core	E2E and cross-plane (User plane / Control plane / Management plane)
Microservices	No	Yes, E2E, all planes
Resource awareness	Only air interface	Yes, all employed resources, including compute, transport, wireless
Trustworthiness	Trustworthy nodes	Trustworthy adaptive services/ network of networks
Ai/ml integration	Over-the-top	Natively integrated
Admission control	Access control	Execution control
Device/node disaggregation	Centralized unit (CU)/ distributed unit (DU), integrated access and backhaul (IAB)	Fully flexible

was a mobile telephone service with very low capacity and a weak connection. Later, we noticed an increase in speed in 2G (14-64Kbps) [48]. The transition from 1G to 2G further shifted the analog network to a digital network. The 2G generation included short message service (SMS) and multimedia messaging service (MMS) technology with a bandwidth of 30–200 kHz [47]. In 3G, the speed was further increased to 2Mbps along with the bandwidth, which ranged from 15 to 20 MHz. This led to vast innovations in mobile technology [47]. Such innovations include technology that enables the “smart” phone to enter our daily lives. Subsequently, the fourth-generation (4G) was developed to have a download speed of 100–300 Mbps, while 5G has a faster download speed. Its throughput speed is planned to reach up to 1 Gbps [47]. This information regarding the gradual evolution from 1G to 5G is provided to compare these mobile technology generations and assess the development of 6G.

2.1. Enhancements in 6G technology

5G is expected to become widely available, laying the groundwork for 6G. When comparing all generations, it is clear that internet speed and coverage increase gradually. The 6G target is to provide global coverage. AI applications will distinguish 6G from previous generations. Although it is still in its early stages, the autonomous 6G network is expected to serve as the backbone of 6G technology. Compared to the current 5G capacity, data rates and security quality will increase, and latency will decrease. 6G is estimated to have a speed of 1–10 Tbps [49]. Its frequency will be higher than all other generations. The frequency generally increases as generations move forward. High transmission rates are indicated by the THz frequency. Because of 6G, latency will be in the range of 10–100 μs, connectivity density will be in the range of 10 devices/km^2, and traffic capacity will be in the range of 1 Gb/s/m^2 [49]. Furthermore, for those new definition KPIs, 6G will improve coverage percentage to 99 %, reliability to 99.9999 %, positioning error from the current meter level to the centimeter level, and receiver sensitivity better than –130dBm. Shown in Table 2, spectrum efficiency and energy efficiency will exponentially increase compared to 5G. 6G promises an unlimited wireless connection. It will be a communication network that will host numerous systems such as communication, metering, storage, computing, control, Global Positioning System (GPS), radar, imaging, and navigation [25,49]. The main features of 6G are summarized in Fig. 1.

2.2. Importance of developing 6G technology

To understand the importance of 6G technology, it is relevant to examine where 6G will be used. For instance, in addition to phones, it is estimated that the density of mobile communication devices will increase. These can be wearable devices, integrated headsets, and implantable sensors [13]. Each new device requires a certain system to communicate as well as several environmental conditions depending on where it is used. Higher quality devices require more advanced environmental conditions, and these conditions are only available in 6G. Despite the enhancements in 4G and 5G technology, it may not be possible to provide seamless, high-quality communication everywhere with existing generations. These generations may still suffer from problems such as high mobility, doppler shift, frequent hand-over, and lack of coverage in some areas [13]. The 6G architecture will solve these issues and provide global coverage [50]. Current communication generations may be insufficient for indoor communication. The number of undeveloped and rural regions are highly populated. 6G technology will be effective in undeveloped rural areas as well as in busy and developed cities. This large-scale communication network will be enabled by terrestrial, airborne, and satellite communications [51,52].

Submarines are also included in the concept of global coverage. This is crucial since most of the world is covered by water. 6G technology must participate in Industry 4.0. Building and factory automation, production, e-health, transportation, agriculture, surveillance, and smart networks all require

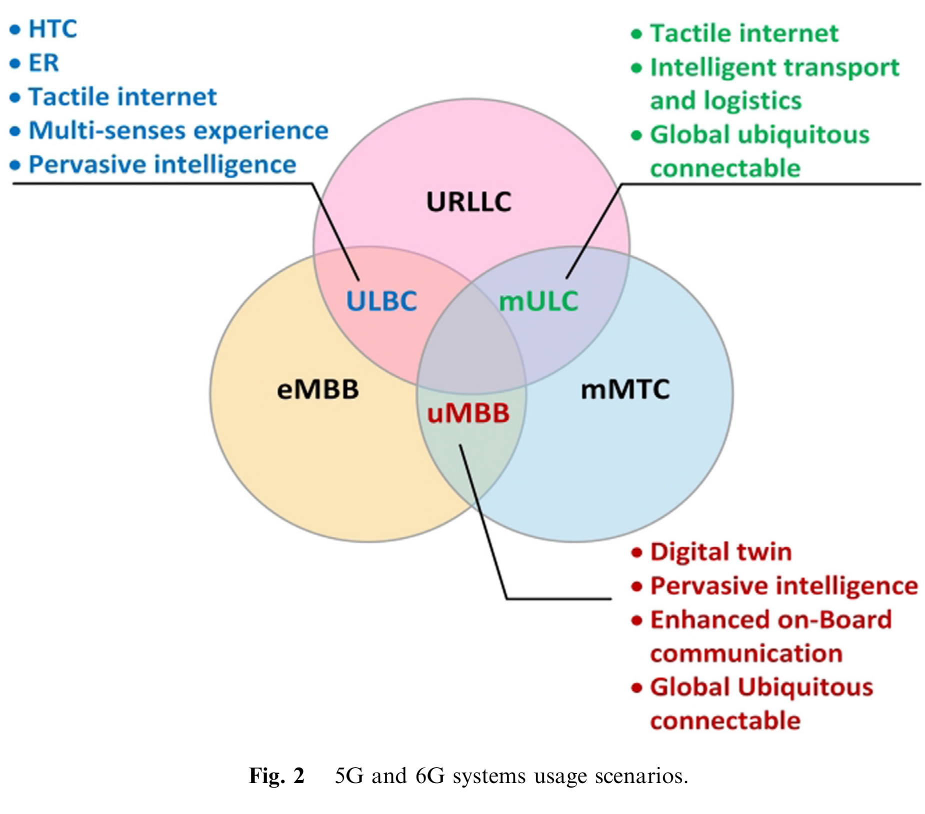

Fig. 2 5G and 6G systems usage scenarios.

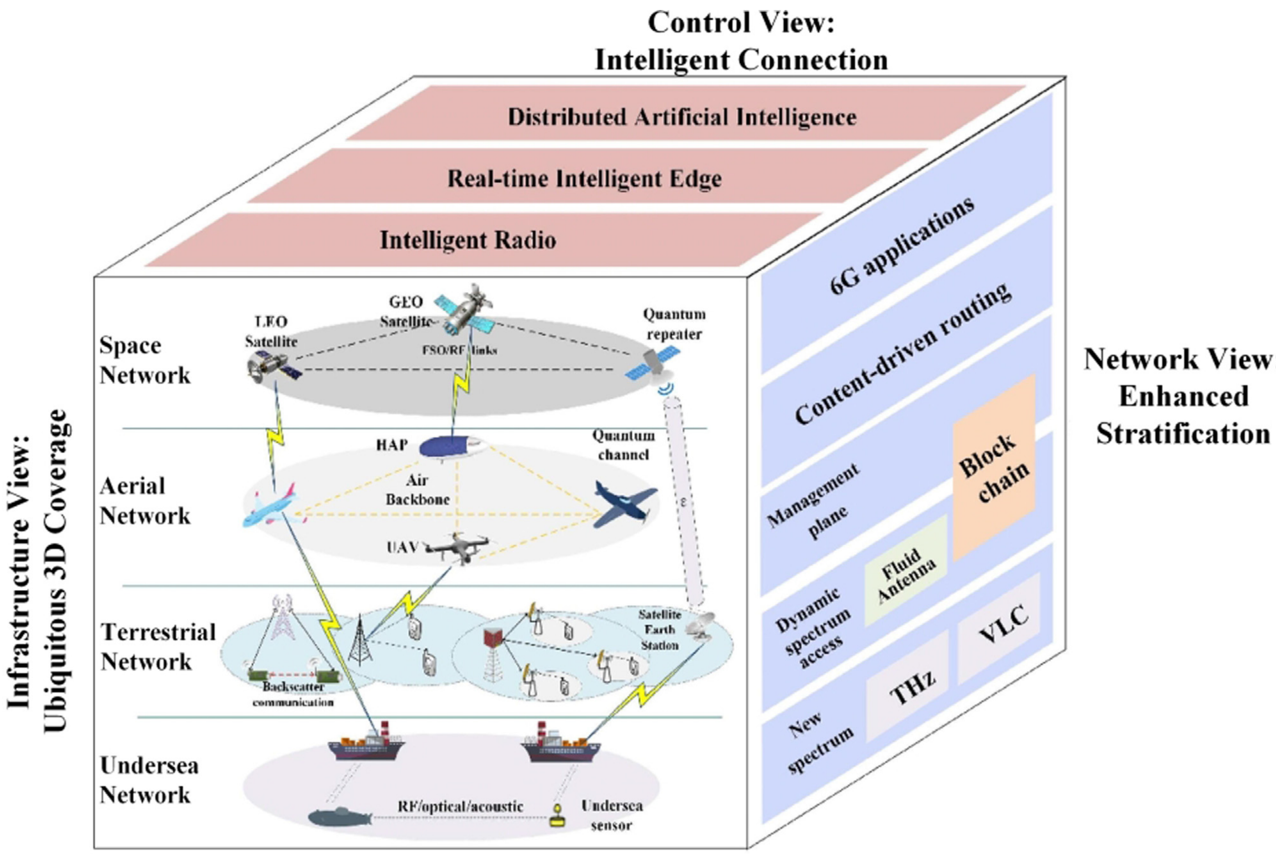

Fig. 3 6G architecture.

6G for enhanced reliability, latency, and broad bandwidth. With the launch of 6G, it is expected that many devices using the internet infrastructure will be included in daily life [53]. The IoE concept provides integration and autonomous coordination between all devices. 6G will provide substantial IoE support. Device autonomization makes life easier for smart societies by providing smart homes, smart cars, and smart factories. It will enable devices to perform several tasks that are currently handled by people today. 6G will further facilitate smart healthcare services since a reliable remote monitoring system will be possible. Reliability, low latency, and a high data rate will even allow remote surgery to take place since medical data can be quickly and conveniently transported [54]. The defense industry will also benefit from 6G technology since high data rates in wireless connections are required for UAVs. The reliability of this connection will be crucial for the defense industry. Therefore, 6G will be much more secure than current generations.

Another contribution of the 6G generation will be the transfer of the five senses (taste, smell, touch, vision, and hearing) to users. This transfer will include a neurological process that will be made possible thanks to wireless brain-computer interactions [32]. The system, known as the brain-computer interference (BCI), will be used to establish a connection between the brain and other devices connected to this system [55]. Haptic communication is a branch of non-verbal and tactile communication. Tactile communication, like other sensory communications, will be supported by the superior features of 6G. AI, virtual reality, 3D media, and IoE-based systems are based on 6G [56].

Table 3 presents a comparison of network features for 4G, 5G, and 6G mobile communication systems. It can be seen that the technical features required by the mentioned applications are available in 6G. Table 4 further elaborates on the main anticipated differences between 5G and 6G network architectures. Adapting to a future digitalized world can only be possible with 6G. Since these innovations will be integrated into every aspect of life and throughout all sectors, they will lead to a new lifestyle. Accordingly, countries will be able to develop further with the use of these innovations.

2.3. Scenarios of usage

The 5G system is planned to meet the most diverse quality of service (QoS) requirements emerging from an extensive variation of vertical services and applications, which mobile subscribers in previous generations had never encountered [57]. To describe 5G, ITU-R M.2083 first recommended three usage scenarios in 2015 [58]:

- **Enhanced mobile broadband (eMBB)** processes human-centric applications for high data rate access to mobile services, data, and multi-media content. This scenario promotes new applications and services across smart devices (smartphones, wearable electronics, tablets). It focuses on

Table 5 List of European research projects beyond 5G and 6G.

Call	Acronym	Project Title	Major Research Topics
ICT-20	5G-ZORRO	Zero-touch security and trust in 5G networks for ubiquitous computing and connectivity.	Security, privacy, distributed ledge technology (DLT), zero-touch automation, E2E network slicing.
	INSPIRE-5G+	Intelligent security and pervasive trust for 5G and beyond.	Trusted multi-tenancy, security, Al, blockchain.
	5G-Clarity	Beyond 5G, multi-tenant private networks that integrate cellular. Wi-Fi and Li-Fi driven by AI and intent-based policy private networks, AI-driven network automation, and intent-based network.	Private networks, AI-driven network automation, and intent-based networking.
	5G-Complete	A centralized network, computational, and storage resource management framework optimized for end-to-end performance in secure 5G multi-technology and multi-tenancy environments.	Computing-storage-network convergence, architecture, post-quantum cryptosystem, fiber-wireless fronthaul.
	ARIADNE	D-band network assisted by AI for Long-Term Evolution of 5G.	D-band meta surfaces, Al-based management.
	TERAWAY	Terahertz technology for ultra-broadband and ultra-wideband operation of backhaul and fronthaul links in systems with SDN management of network and radio resources.	THz, photonics-defined transceiver, backhaul and fronthaul, network, and resource management.
	LOCUS	On-demand localization and analytics embedded in the 5G ecosystem for ubiquitous vertical applications.	Localization and analytics, location-as-a-service.
	MonB5G	Distributed management of network slices in beyond 5G.	Network slice management, zero-touch automation, and Al-assisted security.
lCT-52	Hexa-X	A B5G/6G vision and intelligent fabric of technology enablers connecting the human, physical, and digital worlds.	High frequency, localization and sensing, connected intelligence, Al-driven air interface, 6G architecture
	REINDEER	Hyper diversity in energy efficient radio weaves technology enables resilient interactive applications.	Intelligent surfaces, cell-free wireless access, distributed radio, computing, and storage, channel measurement
	DAEMON	Network intelligence for adaptive and self-learning mobile networks.	Network intelligence, Al, E2E architecture.
	6G brains	Integrate Reinforcement Learning into the Radio Light Network for Massive Connections.	THz, OWC, Al, 3D SLAM, D2D cell-free network, reinforcement learning.
	DEDICAT 6G	Dynamic coverage extension and distributed intelligence for human centric applications with assured security, privacy and trust: from 5G to 6G.	Distributed intelligence, security and privacy, Al, blockchain, smart connectivity,
	AI-edge	A secure and reusable AI platform for edge computing in 5G networks and beyond.	Al for network automation, Al-enabled network applications, edge computing, security.
	MARSAL	ML-based resource management of 5G and beyond, intelligent networks', networking and computing infrastructure	Optical-wireless convergence, fixed-mobile convergence, distributed cell-free, O-RAN, AI, blockchain, secured multi-tenant slicing
	TERAFLOW	Securing autonomic traffic management for Tera of SDN flows	SDN, DLT, ML-based security, cloud-native architecture
	RISE-6G	Intelligent reconfigurable sustainable environments for 6G wireless networks	RIS, architecture and operation for multiple RISs, radio propagation modeling,

broad area coverage to provide smooth access and high capacity in hotspots.

- **Ultra-reliable low latency communication (URLLC)** is a disruptive advancement over the earlier generation networks that placed emphasis on human users. It enables serious mission connection for new applications such as Industry 4, Smart Grid, and self-driving cars, which have stringent requirements for reliability, response time, and availability.
- **Massive machine-type communications (mMTC)** support ultra-high connections with a massive number of connected devices, typically established in IoT scenarios. Devices such as sensors are cheap, consume low power but typically transmit a low volume of data, which tolerates delays.

It can be realized that these 5G usage scenarios cannot fulfill the technical requirements of 6G applications. Therefore, some related research investigated possible usage for 6G via developing the scope of existing usage scenarios as illustrated in Fig. 2. Three novel scenarios are anticipated to satisfy the requirements of 6G use cases, which cover the overlapping domains of 5G scenarios to shape an integral set. To support high-quality onboard communications and worldwide ubiquitous connections, MBB must be available across the entire surface of the Earth in the 6G era, named ubiquitous MBB or ultra-mobile broadband (uMBB).

The uMBB scenario will be the basis of digital twins, enhanced onboard communications, pervasive intelligence, and universal ubiquitous connectability, as the relationship map elaborated in Fig. 2. Moreover, ultra-reliable low latency broadband communications (ULBC) provide applications that not only require URLLC but also extremely high throughput. This scenario is expected to provide an advantage in use cases of holographic type communications (HTC), Tactile, ER, multi-sense experience, the internet, and pervasive intelligence.

Furthermore, the third scenario named "massive ultra-reliable low latency communication" (mULC), integrates the features of both URLLC and mMTC, and thus will enable the deployment of a large number of actuators and sensors in vertical industries. Hence, these three novel scenarios, together with eMBB, URLLC, and mMTC, will complement each other to form a complete set of usage scenarios to support all 6G applications and use cases.

2.4. Architecture of 6G mobile technology

As previously mentioned, current terrestrial network capabilities are far from being available to satisfy the 6G requirements for global coverage. A large-scale network is needed, one that can also integrate non-terrestrial networks to support a variety of applications, such as flying and sailing. The 6G architecture will be cell-free, dimensionally large, and four-tiered. The network tiers include space, air, terrestrial, and sea, as illustrated in Fig. 3 [25]. For example, with the space network tier, space internet services (which can be critical for space travel) will be within the coverage area due to satellites [59]. For the terrestrial tier, data transfer with Tb/s speed will be provided to increase the 6G coverage area with the use of THz frequency bands. The frequency will therefore rise, causing an increase in path loss. The range of 6G will be smaller than current generations. In this case, it will be necessary to employ more base stations, making the 6G network significantly more crowded and dense.

With the use of 5G, the IoT network concept refers to billions of intelligent devices that connect systems, people, and other applications to gather and share data. With 6G, this concept will expand and develop into real-time control and response, not limited to connection and communication relationship detection. The "Tactile Internet" describes the real-time detection, control, access, and operation of virtual objects, as defined by the IEEE 1918.1 Standard [60]. Due to current limitations in resources and detectors, the THz spectral range is not used to its full potential. Photonic solutions have been the forefront technology expected to enable this frequency range for various applications. Photonic techniques are the desired solutions for the production of mmWaves and THz in terms of energy efficiency, bandwidth, and adjustment range. Methods of generating THz frequencies based on photonic heterodyne mixing techniques can overcome the bandwidth limitation of electrical components as well as effectively promote the seamless integration of fiber and wireless network communication. This will make the fiber-THz-fiber streaming communication system a promising choice [55,61]. Visible light communication (VLC) systems are significant for 6G. VLC operates in the 400 THz to 800 THz frequency range. Unlike RF technologies that use antennas in the low THz range, visible light communication relies on lighting sources (specifically, light emitting diodes (LEDs) and image sensors, or photodiode arrays) to communicate with transceivers [62]. In several non-terrestrial scenarios, such as aviation or marine applications, visible light communication outperforms RF technology in terms of propagation performance.

2.5. Related research on 6G technology

In October 2018, the European Commission announced the launch of the ICT-20–2019 call "5G Long Term Evolution" under the eighth Framework Programmes for Research and Technological Development (FPS) being called Horizan 2020. Eight projects, including 5G-COMPLETE [63] and 5G-CLARITY [64], were chosen from a total of 66 proposals and began in early 2020. The accepted projects that were selected through a highly competitive evaluation process in their recent call ICT-52–2020 "Smart Connectivity Beyond 5G" expressly state that their vision is to provide early research activities on 6G.

Table 5 summarizes the details of the ICT-20 and ICT-52 research projects. Following the successful strategy of the 5G Infrastructure Public Private Partnership (5G-PPP) under Horizon 2020, the upcoming Horizon Europe or FP9 research and innovation framework program will focus a large number of efforts and funding on the research and development of 6G and will be structured in the framework of a Public Private Partnership (PPP) "Smart Network & Services." Moreover, in February 2020, the European Commission declared its strategic plan to speed up investments in Europe's "Gigabit Connectivity," including 5G and 6G, in order to shape Europe's digital future [65].

Furthermore, a number of countries have announced and are carrying out innovative plans to deploy 6G research and development projects. South Korea, Finland, China, and the United States are currently at the forefront of 6G research and applications [12]. In 2018, Finland launched research initiatives led by the University of Oulu on the THz Spectrum, AI applications, and localization and sensing [66]. Under the leadership of ITU and the Federal Communications Commission, the United States examined THz spectrum studies, reviewing service requirements and edge intelligence in the 95 GHz–3THz range under the leadership of ITU and the FCC [67]. In the same year, a partnership between the EU and Japan led to relevant studies on the THz spectrum. Research on 6G applications also began under the leadership of South Korea and Samsung with a review of business models, 6G vision, and key features [68]. China further contributed to the literature with their research on 6G conceptualization [43].

Edge intelligence (EI), supported by AI techniques, is considered to be the main missing element in 5G networks, making 6G implementation a key point. Finland has provided a comprehensive explanation as to why edge intelligence is an important element of 6G as well as the leading design principles and technological tools that will drive efforts toward 6G edge intelligence (EI). Currently, EI is the step between 5G and 6G [69].

Finland has worked on 6G edge intelligence, moving towards 5G and future 6G networks. Intelligent solutions using data-driven ML and AI will become crucial to many real-world applications. This will enable more efficient manufacturing, new personal smart device environments and experiences, and urban computing. Finland has focused on topics such as edge computing infrastructure and platforms, data

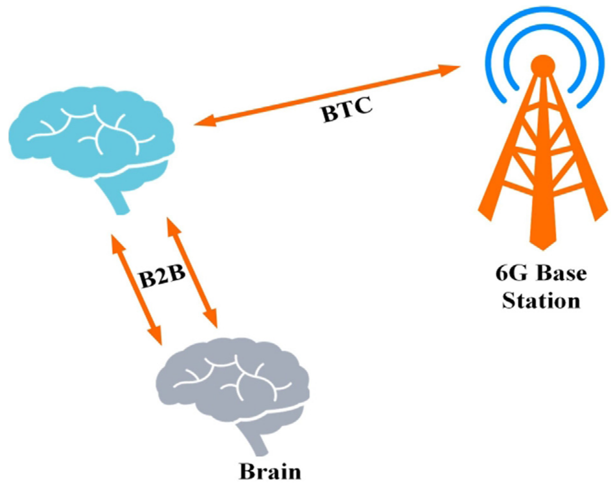

Fig. 4 The wireless interaction between the brain and machine.

and edge network management, software development for the edge, real-time and distributed training of ML and AI algorithms, as well as security, privacy, and pricing. Finland has discussed key facilitators and challenges, identifying crucial research questions for the development of smart edge services. From their work, they envisioned the transition from the internet of things (IoT) to the smart internet of things and drew a goal map for the development of the 6G smart end [66].

By 2030, societies will be digitalized and data-driven. They will be enabled by key verticals such as connected industries, smart transport systems, and smart cities [12,70–72]. Among the main providers are machine type communication (MTC) to cover critical aspects and virtually instant unlimited wireless connectivity. It is clear that some of the more demanding requirements of MTC may not be fully supported by 5G networks [73]. However, as society marches towards 2030, it will lead to new and comprehensive requirements for wireless connectivity in general and MTC in particular. Driven by societal trends, 6G will be an agile and efficient convergent network that serves a range of service classes and a wide variety of key performance indicators (KPIs). At Finland's initiative, the main drivers and requirements of a 6G network optimized for MTC were investigated, revealing different aspects of MTC. The research content is summarized as follows: Key enablers for designing ultralow power receivers and highly efficient sleep modes have been designated to support ultra-low-cost, ultra-low-power, or even passive MTC devices; new service classes that characterize mission critical and dependable MTC in 6G will be supported through multifaceted connectivity and non-cellular centric wireless solutions; potential enablers of long-term secure schemes will consider the heterogeneous requirements and capabilities of MTC devices [73].

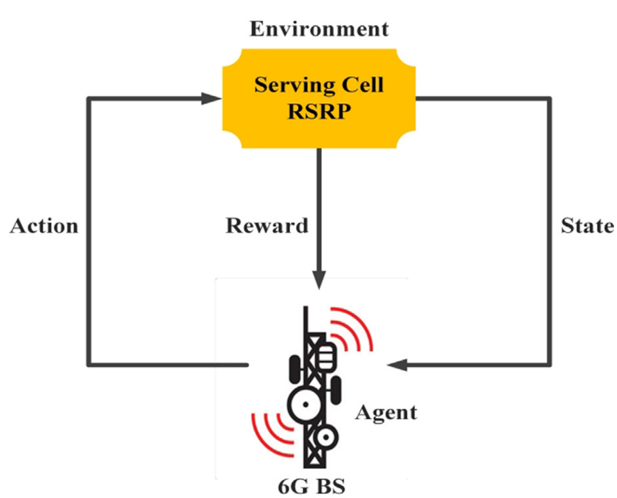

Fig.5 RL-based UAV communication.

With the participation of more than 50 experts, Finland has undertaken studies that shed light on advanced network-related features that will shape the evolution beyond 5G, ultimately leading to the 6G mobile system. They examined the advances and consequences of software evolution and service-based architecture. They also considered a cloud native mobile communication system, the adoption of a new IP architecture that supports high-precision services, and the assessment of key technologies that will reinforce the evolution towards a 6G network. They further explored the different analytics that can be obtained from various segments involved in the delivery of a particular communication service. The benefits of high-precision end-to-end telemetry and cross-segment analytics were further demonstrated [74].

3. Opportunities of 6G mobile technology

6G mobile technology offers various key factors, such as high bandwidth, extremely reliable communication links, increased data transmission rate, low latency, and a suitable environment for AI applications. These factors provide many new application areas in which 6G can be used instead of the former 5G mobile technology. The recent applications cover a wide range, from military applications to personal needs. With the pandemic, personal needs must now be met remotely. The necessity of reliable communication services without compromising high data rates has become more of an issue. This chapter discusses the opportunities and advantages of 6G mobile technology, including key factors and examples.

3.1. Industrial automation

In recent years, the concept of industrial automation has gained increasing attention with the development of Industry 4.0 [75]. Every sector is planning to carry their manufacturing process to a fully automated version. Although the services provided by these sectors are different, their main purpose in automating their systems is the same: to eliminate the human factor from production. The desire to remove the human element from the system is due to the probability of damage that can be caused by humans. In this case, the machines that will play a role in the automation process must be reliable enough to replace humans. For the full automation process, it is obvious that low latency is crucial to avoid issues that can affect systems and thousands of devices. Receiving the response from each module in the system is vital to complete the entire process. Such reliable and fast transmission of data can only be provided by the 6G mobile technology.

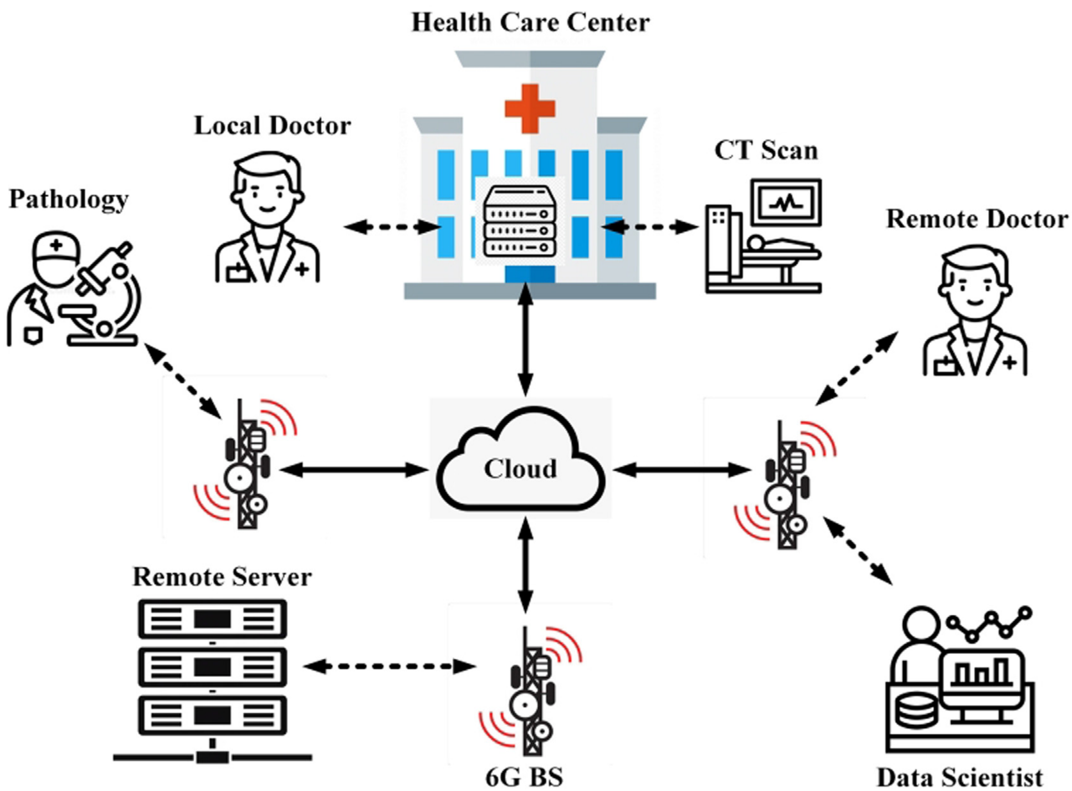

Fig. 6 Remote medical healthcare with 6G mobile technology.

3.2. Internet of space things

The IoST can be considered as an expansion of the IoT to terrestrial applications. The necessity of IoST is based on the lack of flexibility brought by IoT in terms of the type of infrastructure used. Another limitation is the issue of coverage, which reveals the need for new technology. The construction expenditure can be unaffordable, especially in remote areas such as the North and South poles. Communication between these remote areas or satellites is possible with the 6G mobile technology since it increases the data transmission rate by up to 100 Gbps and has high bandwidth coverage. With this novel technology, the space data collected by satellites can be transmitted with no latency problems, enabling us to make various observations that can carry our technology and knowledge in space one step further [6,76].

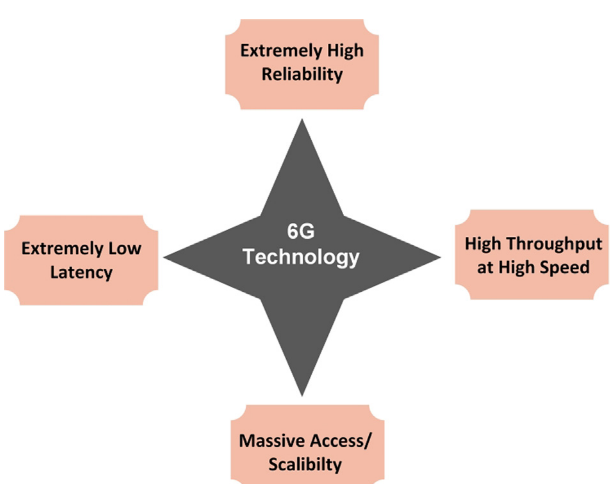

Fig. 7 Key features of autonomous driving with 6G mobile technology.

3.3. Communication between brain and machine

The brain-machine interface is an approach to analyzing brain signals transmitted to digital devices and interpreting them into various actions or commands. The approximate estimate of the entire brain recording demand is about 100 Gbits/s, which is incompatible with current and near-term 5G networks. Because brain-machine interface (BMI) technology is still in its early stages, this speed requirement is merely an assumption. Considering that future BMI and signal types to be transmitted from cells have not yet been discovered, this data speed estimation is likely to increase. It is clear that the speed of data transmission provided by 6G mobile technology is essential for BMI systems [77]. The second vital requirement of BMI is reliability for constant data transmission [78,79]. The health sector is the one that will benefit the most from BMI systems. However, any network disruption can be fatal for patients. For instance, epileptic patients must be constantly observed since seizures can give rise to permanent infirmity unless the data transmission between the brain cells and the doctor is performed without any interruption. The solution to addressing the reliability of current wireless communication technologies would be intelligent reflecting surfaces, which are still at an infancy stage in development.

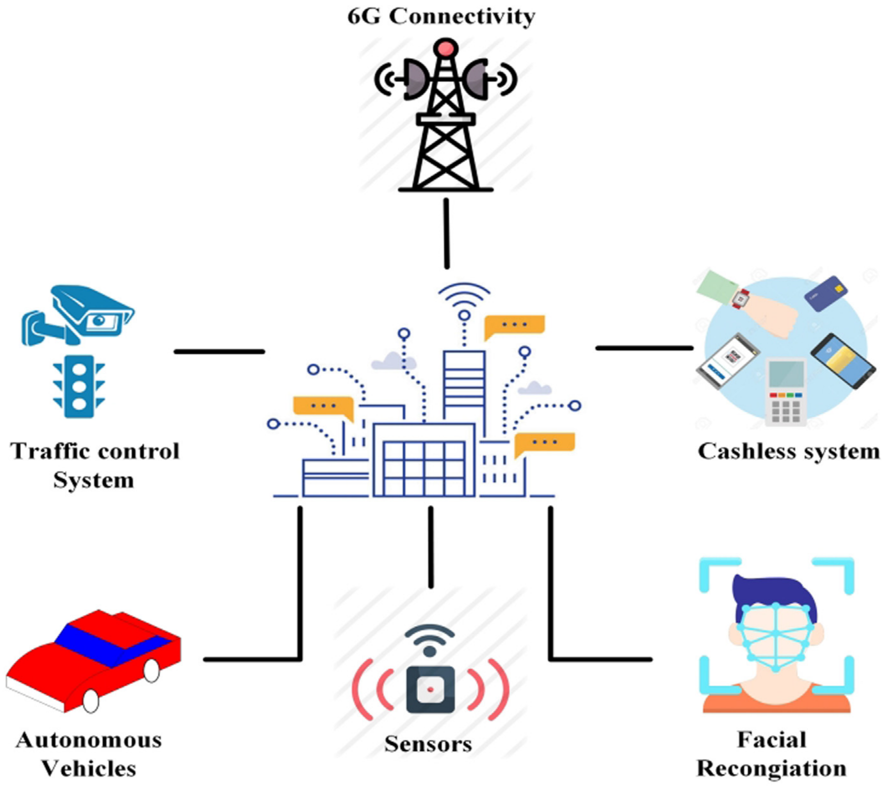

Fig. 8 Smart cities using 6G mobile technology.

The importance of a constant data rate can be achieved by 6G. However, another undesirable problem is latency, since the main goal of the BMI system is to allow constant and daily use by patients [80]. Vast sensing is promising in 6G, which can work with future BMI technology that envisions hundreds or thousands of nano-scale systems interacting with neuronal cells [77]. Fig. 4 presents an illustration of different types of BTC communications in 6G systems.

3.4. Drones

Drones play a significant role in several applications, such as transportation, package delivery, surveillance, and media production [35]. With many possible application areas, secure, reliable, and stable wireless communication are required to ensure safe control and operation of drones. With 6G mobile technology, AI-based solutions can be implemented to address various problems, such as connectivity issues in the sky.

One of the biggest challenges in the application of drones is the issue of seamless connectivity in the sky. Fragmented reference signal received power (RSRP) can cause radio link failure, frequent handovers, and ping-pong handover events [2,81–87]. To provide continuous UAV connectivity in the sky, reinforcement learning is a potential solution for aiding the development of optimal handover rules and ensuring stable communication at minimum handover cost. According to [88], the conventional method of drone communication (where drones connect to the BS with the strongest RSRP value) has a remarkable number of handovers. The reinforcement learning (RL)-based solution can significantly reduce that number since it captures the trade-off between RSRP and the number of handovers [36]. Fig. 5 illustrates the RL-based schema for drone communication in the sky.

As seen in Fig. 5, the RL-based solution takes the base station as the agent, and the combination of RSRP and the cost of handover as the reward function. The agent interacts with the environment and moves to a new state from the current state according to the reward/feedback received from its action in the current state.

3.5. Remote medical operations

With the COVID-19 pandemic, the vulnerabilities of the current healthcare system have become apparent. As the number of patients suffering from the coronavirus increases, the lack of sufficient medical care resulting from an inadequate number of medical staff is now evident. Transportation, a crucial aspect during serious injuries, is also unsatisfactory with current technology.

According to [89], most patients die in ambulances on their way to the hospital, before the ambulance arrives at their destination. Telesurgery, expected to be a widespread solution to many diseases in the future, requires real-time communication that cannot be met by the current 5G technology. Telesurgery, or remote medical care, is the remedy for medical care and transportation issues, taking the needs of physical mediums out of the equation. Remote medical care requires communication with high data rates and stable connectivity. Remote healthcare requirements can be fulfilled with 6G mobile technology since it will use the terahertz signal for data transmission with high data rates exceeding 1 Tbps and a low end-to-end delay, which is lower than 1 ms. Further advancements

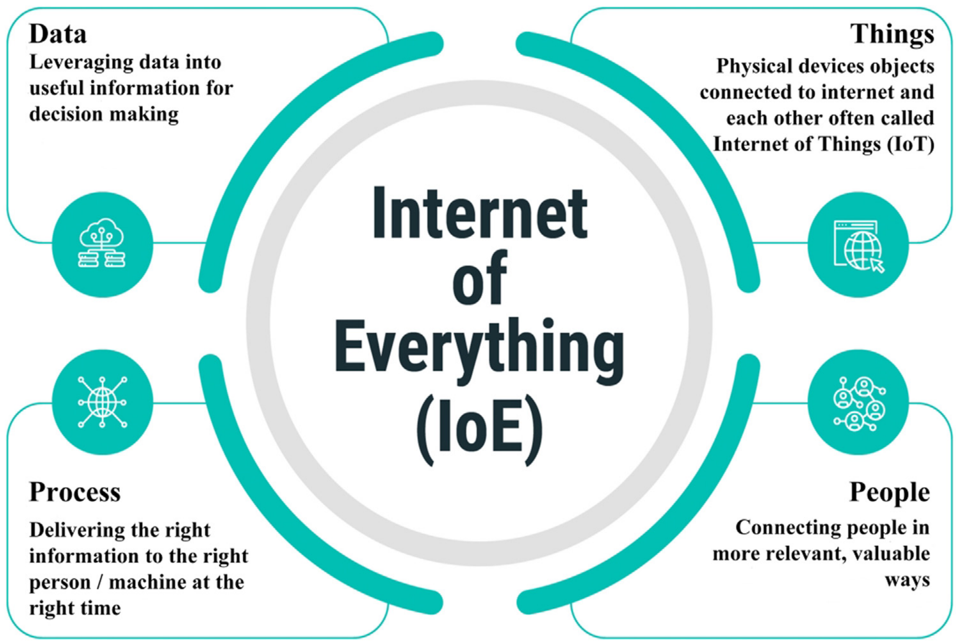

Fig. 9 IoE with 6G mobile technology.

can be made in the health sector, such as holographic communication, which supports more interactive verbal guidance, or tactile/haptic communication, in which the doctor can tele-assist during surgery. Fig. 6 represents the 6G communication model for remote medical healthcare.

3.6. Autonomous vehicles and robotics

Connected autonomous vehicles (CAVs) are an important vertical industry in 6G. The implementation of connected robotics and autonomous vehicles is aided by the deployment of 6G systems. With 6G providing a higher spectrum with a shorter wavelength, more accurate sensing and positioning resolutions are possible. Increased data throughput can be achieved by using higher frequency bands, thereby enhancing beamforming directionality.

The THz band, which usually includes a frequency band in the range of 100 GHz to 1 THz, is needed for high-speed links that are crucial for communication between CAVs and the infrastructure. This will lead to remote driving, perception of raw sensor data, and mobile edge intelligence [30]. The THz band is also beneficial for sensing, positioning, and 3D imaging. Since THz signals have a short wavelength, antenna size and separation distance can be drastically decreased, allowing for the installation of a large antenna array in mobile devices and base stations.

Large antenna arrays can be precisely positioned so that less localization error can be achieved compared to what is usually experienced by traditional GPS satellite-based positioning. High carrier frequencies can also be used for radio frequency sensing, providing precise location and object detection. Overall, 6G will enable several essential features such as low latency, high-speed data-based communication, increased reliability, and wider frequency bands for fully autonomous driving. Fig. 7 presents the key features of 6G technology for autonomous vehicles.

3.7. Smart cities

The Smart Cities concept dates back to 1994. It has become more necessary with the presence of the COVID-19 pandemic since many human practices (such as education or cultural activities) are forced to transfer to digital platforms. The attempt to make cities smarter is listed as the use of autonomous vehicles, sensors, and cameras for traffic control, recognition systems, and cashless systems in the financial sector. These attempts require faster connectivity, especially in AI-based solutions such as the internet of things. 6G mobile technology promises faster connections, higher broadband speeds, and quicker bandwidth capabilities required for the above-mentioned services.

The connectivity capabilities offered by 6G mobile technology are one thousand times faster than those of 5G, which currently allows users to access speeds of 1–10 Gbps. Although 5G mobile technology is beneficial for communication technologies such as IoT, 6G allows the full exploitation of AI technology. With the contributions of 6G to AI, customer services offered by IoT will exponentially rise, providing easy access to personal data or environmental data such as weather conditions, quality of food, or air pollution in urban areas. Additionally, the variety of interactions between these devices and humans will expand, resulting in relatively cheaper and faster access to personal or environmental data. The necessity of making our cities smarter to easily access both environmental and personal data is now more essential to our lives than in the past due to the pandemic [90]. Fig. 8 provides an overview of the smart city concept.

3.8. Internet of everything

IoE is the networked communication of humans, processes, files, and objects. Many claim that 99.4 % of solid objects in the future will be included in the IoE concept [91]. The main difference between IoT and IoE is that IoT can be defined as the wireless communication between simple physical objects such as phones, computers, or the alarm systems in our houses. IoE refers to the communication of processes and people other than these solid objects. Everything initially began online. IoE is gaining great amounts of attention on a daily basis. The current 5G technology can meet IoT requirements but not those of the IoE. Since IoE covers a larger number of properties compared to IoT, its requirements will be significantly more. For instance, seamless connectivity and wider bandwidth are required for IoE considering the number of devices and processes that are expected to communicate with each other. IoE technology will also be used in emergency situations (such as theft and break-ins). Therefore, data transmission must be high speed and continuous. These requirements can be fulfilled with the 6G mobile technology. It is expected that IoE technology will be used in smart industries, ranging from smartphones to smart cities in the future [92]. Fig. 9 provides an overview of the IoE technology.

3.9. Extended reality

The high bandwidth and reduced latency of the current 5G mobile technology have already increased the VR/AR experiences of consumers. However, a number of issues are present with VR in the 5G network, which must be addressed in the 6G network [32]. A major issue would be latency. The resulting ambiguity causes even more problems. Although deploying VR/AR via cloud storage allows it to become more compact and accessible, files must be compressed for 5G bandwidth. Transferring massive amounts of lossless images or videos in real-time would have to wait until the 6G network is implemented. The dynamic VR/AR experience can be enhanced even further using 6G networks. To gather sensory data and provide input to consumers, multiple sensors will be used [30]. In 6G networks, extended reality (XR) is likely to combine standard URLLC with eMBB, or mobile broad bandwidth and low latency (MBBLL) [12]. Malicious actions, access management, and internal contact are among the most notable protection and privacy problems with URLLC and eMBB in multisensory XR applications. To provide the ability for mass connectivity to XR users in the 6G network, Al et al. devised a new multiple-access approach called DOMA, which can be used in multisensory XR implementations.

4. Enabling technologies for 6G

Based on the technologies implemented in previous mobile communication systems, the 6G network will mainly be constructed according to the 5G architecture, taking advantage of the benefits accomplished in 5G [7,32]. The 6G system will include various technologies, some will be enhanced versions of the 5G architecture, while will be others completely innovative. This section discusses the promising new techniques in 6G technology. THz communications [93] and visible light communication [37] are significant techniques for improving the 6G's system bandwidth, free duplexing, and spectrum sharing. The security and efficiency of standard spectrum sharing can be enhanced by blockchain [94]. Spectrum efficiency can also be improved by MIMO [95] and OAM [96], in which numerous parallel data streams are multiplexed on a similar frequency channel. Computing efficiency that provides strong security for 6G can be maintained by quantum communication (QC) and quantum ML (QML) [5,97].

4.1. Artificial intelligence

Several researchers and industries have already begun working on the next network generation, discussing technologies that will make 6G possible after the deployment of 5G. AI, the technological trend of today, provides several beneficial features for 6G development. AI will play a key role in the advancement of the 6G network structure due to the intelligent use offered by 6G's applications and features for many fields such as architecture, computing, storage, etc. Smart analysis techniques using AI can be implemented in the 6G network. One method would be descriptive analysis, which can be used for better access of data history and network operations. Predictive analytics provides future predictions using collected data and diagnostic analytics, which are vital for increasing network security and providing autonomous detection. Prescriptive analytics applies these predictions to provide several attributions [68,98]. AI also enables closed-loop optimization to wireless 6G networks. In this technique, the user acts in accordance with device feedback. By maintaining end-to-end collective optimization at the system layer, AI can further be implemented to optimize wireless communication systems. This intelligent layer offers numerous possibilities, such as self-optimization, self-learning, and data collection [68]. The examples briefly explained here are only a small part of the widespread applications of AI technologies and the innovations they will bring to the 6G network structure.

4.2. Machine learning

Machine Learning (ML) is one of the most crucial technologies when it comes to self-learning and decision making. This AI-based technology is a computational system that develops mathematical models by recognizing system behaviors and properties, enabling machines to learn without programming. ML algorithms need data collected from many different sources. They use the collected data to optimize the layer algorithms, such as the physical layer and higher layers [99,100]. Wireless communication channels can sometimes lead to security problems. ML will enable the device to learn to increase data privacy and security by learning from its decision making and predicting features. Based on the artificial neural network method, deep learning is an application that can quickly solve computational problems by reaching resources containing large amounts of information. It is a strong technique for 6G's physical layer due to its rapid iterative operations. It can solve maximization problems, reduce computational delay, increase power efficiency, and several other features [99]. ML technology combined with AI will become key in the path towards 6G technology. Probabilistic ML and Bayesian inference methods will provide the theory-based framework with data-rich 6G applications to model high-dimensional and complex real-world predictions. Using ML to design self-aware and self-adaptive communication networks is substantial for the 6G network structure, serving as a flexible and dynamic security layer [99]. ML will also enable automation management for dynamic mobile networks, which will boost power usage, operation, network configuration, and network performance.

4.3. Terahertz communication

It is necessary to use high frequencies and wide bandwidths in wireless communication systems to develop communication networks. Terahertz band communication can enable high data rates and wide bandwidth for communication systems, making it a promising technology for 6G. The THz spectrum is the region between mmWave and far-infrared (IR). It offers higher transmission bandwidth compared to mmWaves and has a more favorable propagation setting than IR. THz communication can be used in various technological fields, such as indoor wireless mobile networks, nanoscale communication, and space communication applications. Intelligent Reflective Surfaces, ultra-massive MIMO, and integrated access can further boost THz communication. Although THz communication system components are difficult to design with the THz antennas, they do provide numerous advantages, such as high gain and rapid beam scanning [17]. The main objective of Subterahertz communication is to increase spectral efficiency using higher MIMO technologies, achieving a Tb/s level data transmission rate that goes far beyond 5G. First-generation Subterahertz communications provide uncomplicated modulation schemes, antenna architectures with wide bandwidth, low spectral efficiency for short-distance communication, power efficiency, simple signal processing, and coding techniques [11]. 6G will be an ultra-dense network in terms of the increase in connected machines and device quantities. THz communication can meet this massive capacity requirement [101]. It possesses far richer spectrum resources than lower frequency bands, making it advantageous for several reasons. The first advantage is that it will satisfy 6G's huge bandwidth demand by providing up to hundreds of gigahertz, reaching several terabits per second. The second advantage is the integration of a larger number of antenna elements into a single base station since wavelength is inversely proportional to frequency and antenna size. More than 10,000 small antennae are expected to be deployed in base stations. They are capable of handling path loss by generating super-narrow beams that reach greater throughputs, simultaneously communicating with more users. Lastly, high directional antenna elements help reduce co-channel interference and prevent eavesdropping during communication, thereby providing better security [25]. Considering the data-rate processing features, Terahertz communication is a strategic enabler for 6G if system complexity and power consumption disadvantages are solved in coming years.

4.4. Visual light communication

The Visual Light Communication (VLC) system is another key technology that must be highlighted since it can provide fiber-optic-like transmission. Optical fiber is a very flexible and thin silica-based medium that uses light for data transmission. Since fiber optic transmits light, the transmission rate and bandwidth are higher than several other methods. Although different types and sizes of optical fibers are present, the transmission rate for every fiber type exceeds the 1 Gbps level [102]. VLC technology employs visible light and offers terahertz level bandwidth, high-frequency reuse, complementary unlicensed spectrum, and no electromagnetic interference [11,37]. VLC development can meet the performance requirements of 5G and make terabit rate data transmission possible for 6G. High-speed data links for personal use and vehicle-to-vehicle communication producing VLC can be attained by light-sensitive devices such as light-emitting diodes, reaching a gigabit level transmission rate. Commercial LED using VLC systems have narrow bandwidth. The system requires bandwidth enhancements and more efficient MIMO system designs in VLC due to limited diversity gains and complex designing processes [17]. Despite these challenges, VLC can produce high-speed data links for personal use and vehicle-to-vehicle communication. Researchers have stated that development in Visual Light Communication can adequately meet the performance needs of 5G and make Terabit data transmission rates possible for 6G by 2027. Thousands of LED active sources will indicate the capacity of the short-range transmission rate [11].

4.5. Multi-access edge computing

As the world becomes more connected, components and systems within the network are also changing. Multi-access edge computing (MEC) will enable the integration of application-oriented capabilities into the 6G network structure [103]. MEC deploys and manages dispersed computing, caching, network communication, and data analysis processes at the edge of the cellular network. Applications that employ IoT derived MEC technology from fog computing aim to use cloud computing. MEC allows rapid decision-making and signal processing through collected data. Decreasing end-to-end latency for the communication link is one of the main goals for various emerging technologies. MEC's intelligent data elimination and data processing features significantly reduce end-to-end latency [70]. Efficiently managing the communication network and resources is the main aspect of the optimization process. By integrating MEC into the network system, layer complexity can be reduced. Centralized resource allocation can also serve as a resource management mechanism. With the implementation of MEC capabilities and vertical-oriented services combined with ML, a dynamically changing and self-optimizing machine type communication (MTC) network can be generated. Network slicing in MEC has been a focal point in numerous studies. It serves as one of the slicing structures in the 5G network and can be applied to 6G. Network slicing offers a flexible and dynamic framework [104]. MEC is therefore a critical technology for 6G. It offers rapid and localized data processing in security, vehicle-based communications, energy usage efficiency, and network framework flexibility.

4.6. Machine type communication

6G will be the first wireless standard to connect numerous users throughout different industry levels, adequately responding to growing communication needs. Various sectors will support 6G-based digitalization using verticals through machine-type communication, as previously mentioned. The smooth operation of a multi-operator system within the vertical sector is not limited to providing connection during transmission. It can further ensure the compatibility of various information technology systems of various units contained in

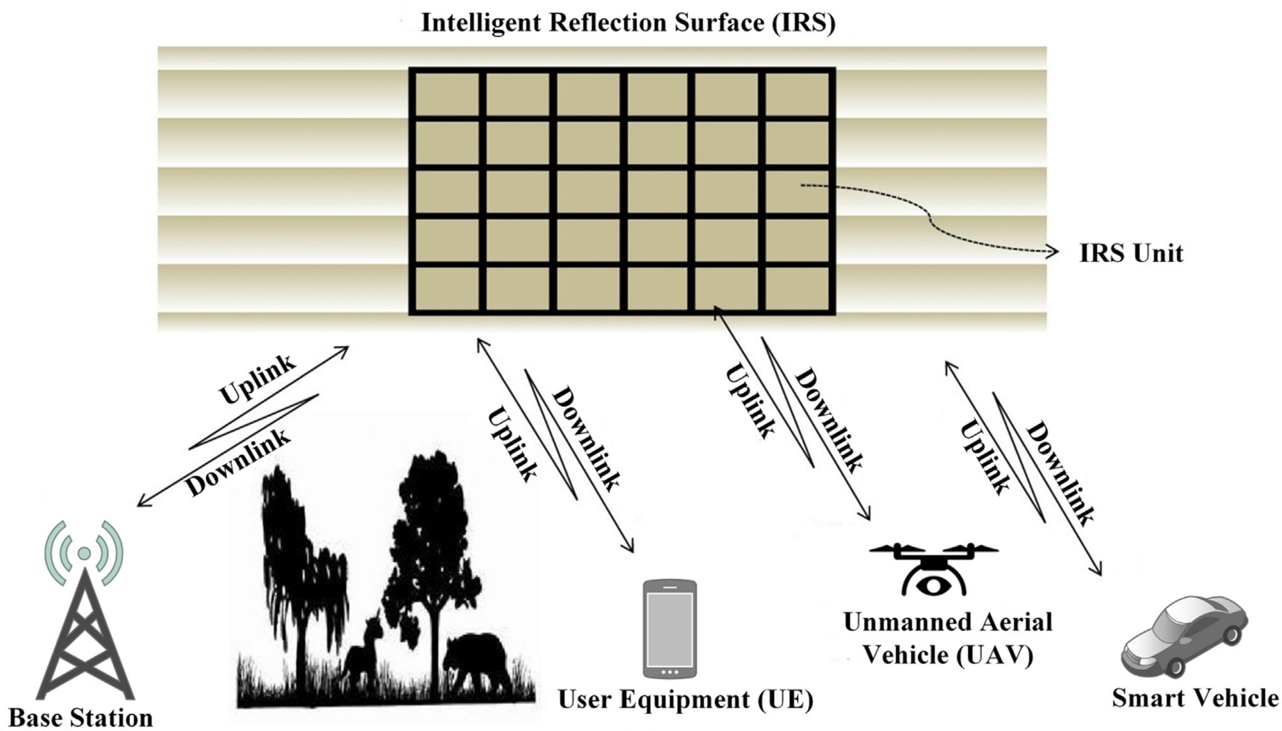

Fig. 10 Intelligent reflective surfaces.

any data [70]. The direct communication between devices using wired or wireless communication channels is called " machine type communication " (MTC). The challenges of MTC implementation are low latency and high reliability requirements. Network function virtualization (NFV) and software-defined networks (SDNs) are some of the technologies that meet the requirements of verticals used in MTC. NFV is a network architecture concept that creates a communication network by connecting network building blocks using virtualization techniques. SDN is a network management technology that creates cloud computing-like network structures to increase network performance and security. NFV and SDN are primary facilitators for addressing the demand for broadband connectivity with low-cost and adjustable implementations [18,105,106]. Designing a core network with a flexible, dynamic, simple, and unified system to serve the wide-ranging needs of different vertical sectors will be necessary for the 6G structure [69]. Implementing computer-based MTC solutions will be a milestone for the development of 6G in the concepts of network scalability, reliability, latency, and efficiency.

4.7. Low earth orbit satellite communication

Space exploration that integrates satellite capacity into independent satellite and terrestrial networks will create innovative opportunities. Such research will improve certain issues such as efficient data transmission, resource optimization, emergency disaster recovery, and uninterrupted high-quality communication in remote areas. The low earth orbit (LEO) system, which has attracted attention for satellite communication, can provide frequency reuse and efficiency by supporting coverage for the entire earth's surface. Three-dimensional coverage with the implementation of on-earth infrastructure and aerial platforms is another research area for 6G technology [107]. Satellite communication's support of mmWaves was first noticed by 3GPP and its use in satellite deployment scenarios. Due to the great distance between the satellite and the earth's surface, the delay and mmWave path loss will inevitably be high. Despite these disadvantages, mmWaves offer high bandwidths and increased directivity with point-to-point satellite links. Satellite communication architectures presents several advancements in terms of cost minimization and heterogeneous satellite network structures for better coverage. In terrestrial terminals, network slicing, NFV, and SDN are combined to facilitate the integration of different technologies into the same platform, enabling flexibility, automation, and agility [107]. The integration of terrestrial and non-terrestrial technologies in cellular communication provides several benefits, such as communication resilience, resource optimization on parallel backhaul links, efficient data broadcasting and relaying, QoS enhancement through edge computing, and communication mobility. Various organizations now recognize that highly directional satellite communication at mmWaves is an essential technology for 6G communication due to its advantages, especially its high capacity for wide coverage [108–113].

4.8. Orbital angular momentum technique

As 6G research continues, increasing channel capacity and maximizing spectrum efficiency will be the main research focus. The angular momentum of electromagnetic waves is a recent topic of interest. Orbital Angular Momentum (OAM) is a new technique in wireless modulation that uses wavefronts with helictical phases, also known as vortex electromagnetic waves. The fact that different modes of OAM are perpendicular to each other enables multiplexing and demultiplexing, offering a new capacity increase for 6G. Long-distance propagation beams are preferred to be convergent for effective transmission. However, OAM beams exhibit a divergent structure. Although it is used in line of sight (LOS) environments, the use of OAM waves in non-line of sight (NLOS) environments is still seen as a problem. Misalignments between transmitters and receivers in practical wireless systems are an issue in the separation of OAM-modes [17]. OAM, on the other hand, offers three major benefits: high spectral efficiency via OAM modes, support for multiple access, and high reliability for anti-jamming due to frequency sharing in the wireless network [114]. The OAM research field has been limited to optical communication, but investigation has now extended to the Terahertz, mmWave, and low-frequency communication fields. OAM is still under development. Combining the OAM technique with advanced channel coding and frequency sharing methods will enhance the effectiveness of the OAM system. Despite the present issues mentioned, OAM is still undergoing development. It will be an important technique for the 6G wireless system.

4.9. Cognitive radio

As wireless data traffic grows day by day, more studies on the full use of low-frequency bands are needed, such as terahertz communication and VLC technologies, which will provide a significant spectrum increase in 6G research. In 5G and beyond technologies, efficient spectrum usage remains an essential factor. Cognitive Radio (CR) applies spectrum sensing and interference management techniques to share the same spectrum within the wireless system, thereby ensuring effective spectrum usage. Symbiotic Radio (SR), one of the latest developments in CR, uses multiple subsystems of a heterogeneous wireless communication system. It is a favorable technique for 6G due to its efficient use of resources and effective transmission by intelligently connecting subsystems. 6G technology can be utilized techniques such as inter-device communication, spectrum sharing, multi-user access, and full-duplex communication. Flexible and intelligent spectrum usage can be provided by combining technologies that are frequently used today [17]. The main objective of the intelligent SR, a new wireless network model, is to increase the communication system's performance by using inter-subsystem cooperation. Subsystems that can have different symbiotic mechanisms are asked to investigate information and transmission limits using various methods. Despite the advantages of intelligent SR, studies are still in their infancy stage. Adequate energy usage remains crucial for 6G to enhance spectrum efficiency, as provided by CR and SR techniques.

4.10. Intelligent reflective surfaces

Intelligent reflective surfaces (IRS), as shown in Fig. 10, are one of the most recent research areas in communication technology. These surfaces allow incoming electromagnetic waves to be reflected in the desired direction thanks to the array system consisting of really small reflective units. To eliminate the factors that affect the communication quality between the transmitter and the receiver, the IRS surfaces are placed in the communication environment to increase communication quality by providing phase differences to the incident wave. The basic idea of IRS is to have an intelligent surface capable

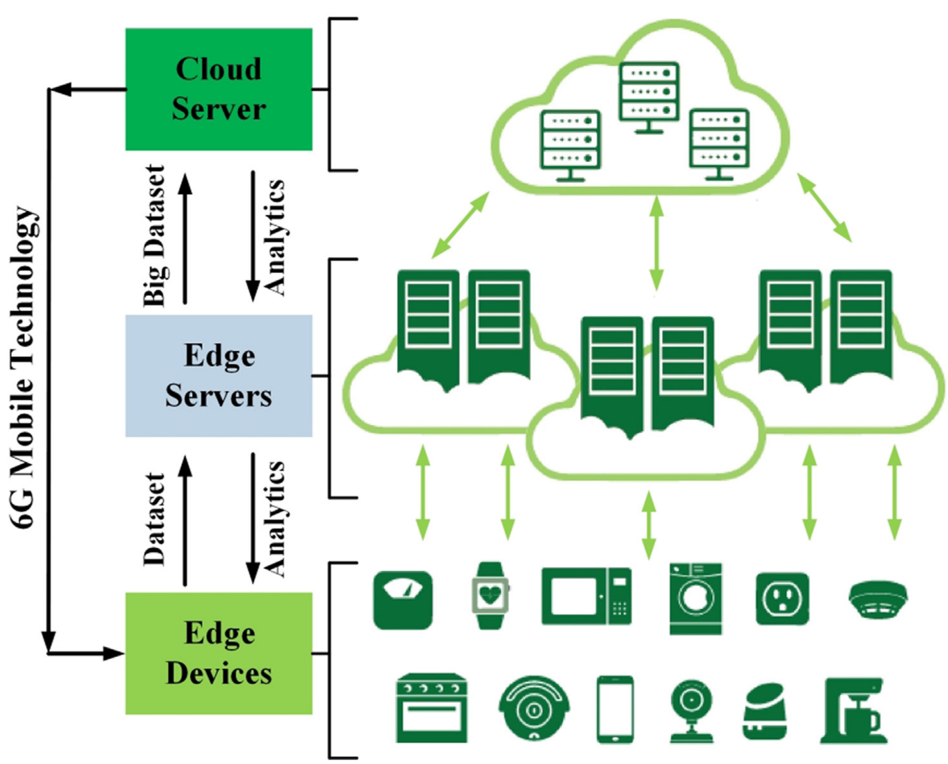

Fig. 11 Edge computing.

of properly reflecting the transmitted signal directly to the user by configuring the phase of reflected waves with the use of software. The IRS also employs numerous low-cost and low-power passive elements in order to reflect incoming signals with controllable phase shifts without any extra power consumption or modulation/demodulation necessities. The IRS will be very useful in deep-fade and non-line-of-sight (NLOS) environments where the signal is unable to reach the end user with enough power. They can be placed on significant points such as high buildings, advertisement panels, and vehicles (cars, UAVs). The essential benefit of IRS is that it can enhance the signal-to-interference-plus-noise-ratio (SINR) without altering the infrastructure or hardware of the communication network. Overall, IRS improves and expands opportunities for 6G communication systems [115].

Studies have shown that applications such as beam steering, beam forming, and multi-user communication can be performed using the phase difference in the units. Various technologies, such as deep learning and deep neural networks, can be combined with the IRS technology to make the system software-based [116]. To illustrate, units can be learned through the deep neural network connected to the IRS controller. Effective interaction with an incident wave can also be achieved using deep learning. Collectively, the communication channels will improve with the IRS. When considering IRS technology with massive multi-input multi-output (MIMO) technology (used to increase spectral efficiency), it is clear that the key role played by MIMO for 5G will also be performed by IRS for 6G. The difference between IRS and MIMO is the use of the wireless communication channel and tuning it to increase efficiency. The IRS will enable the implementation of massive MIMO technology as well as increase the information-transfer capability of the communication system [117].

4.11. Wireless energy transfer

In 6G, wireless energy transmission (WET) can be used to provide enough power to batteries in several devices, such as smartphones and sensors. The 6G network is designed to accommodate large connectivity of up to 10 devices per m3. WET is an appealing technology that can wirelessly and sustainably power IoT networks. Aside from connecting a large number of devices, WET improves the durability of IoT devices, reduces battery waste, simplifies maintenance and servicing, and allows for network-wide reduction of emissions footprint and deployment stability [118,119].

In WET applications, seamless and continuous communication requirements are expected to be met with 6G mobile technology, which is necessary for the enormous number of connected IoT devices. Since wireless information and energy transmission (WIET) applies the same fields and waves as communication networks, the base stations in 6G will be used to transfer electricity. WIET is a cutting-edge technology that will enable the development of battery-free mobile devices, wireless network charging, and the extension of battery life in other devices [30].

4.12. Edge intelligence

The requirement for rapid and dependable data access can be met by centralized cloud computing, which involves the installation of high-end servers and large storage systems for scalable computing. The solution of centralized cloud computing raises the issues of security and latency, which are highly crucial in autonomous vehicle devices, military applications such as drone communications, augmented reality, and medical applications like telesurgery. Considering the disadvantages of centralized cloud computing, edge computing is introduced with low-latency rates and can be performed on mobile devices or near data sources. Computation near user devices provides low-latency and lower bandwidth requirements since data will not need to be transferred to the server. In this way, computation at the server can be considered a better choice in terms of data privacy and the amount of work processed at the user device. Data privacy is at risk when users are on their devices, since attackers have more opportunities to hack the system when numerous devices are connected to servers. Although 5G mobile technology offers reliable communication with low latency, it cannot meet the above-mentioned requirements. 6G mobile technology can be considered perfect solution due to its ultra-low latency, ultra-reliability, high data transmission speed, and high mobility of 1000 km/h [120].

A more advanced solution for low-latency, high storage systems, and increased computation burden would be edge intelligence, which is an AI-based solution. It allows the edge server to perform important and complex tasks right at the edge node. Scalable and efficient computation is necessary to manipulate deep learning algorithms for solving complex intelligence problems. This necessitates ultra-low latency, high speed, and seamless connectivity, as previously mentioned. The future 6G wireless networking system will accept peak data rates of up to 1 Tbps. Considering the aforementioned requirements of edge intelligence and the contributions of 6G mobile technology (an upgraded version of 5G mobile technology), the upcoming advancements will become life-saving technology for applications where milliseconds are critical. Fig. 11 presents the flowchart of edge computing.

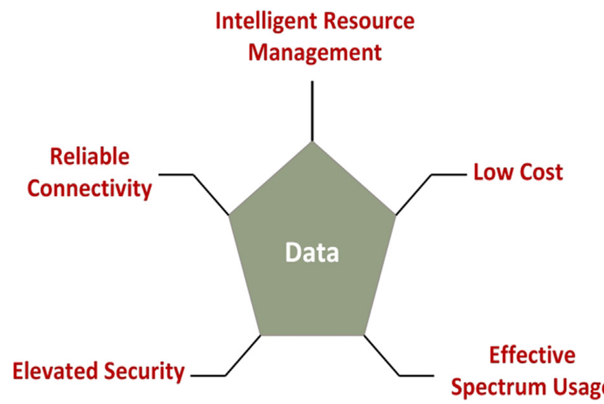

Fig. 12 Advantages of 6G on Blockchain technology.

4.13. Free duplexing and spectrum sharing (FDSS)

Duplexing is communication between the mobile user and the base station where data is simultaneously sent and received by two ends. Some duplexing techniques are employed to prevent interference by different users using the same resources. In older generations (1G-4G) frequency division duplexing

(FDD) and time division duplexing (TDD) have been used where different frequencies or time slots are dedicated to users. However, the division of the spectrum or time does lead to severe inefficiency due to the decreased capacity of each device that has more users. 6G solves this problem with its innovations, enabling users to utilize all resources (i.e., frequency, time, and space) with a full free duplex system. This is a significant leap in terms of low latency and high throughput.

Today, governments allocate spectrum to operators. An operator is allowed to use its own spectrum but not intrude on the spectrum of others. 6G can change this approach and enable free spectrum sharing with the help of AI and blockchain technologies. Dynamic control of network resources can be achieved by advanced spectrum monitoring and spectrum management techniques [115].

Non-orthogonal multiple access (NOMA) is proposed as a free spectrum sharing technique. Compared to OFDMA (used in current 4G systems), NOMA has tremendous potential, such as low latency, greater spectrum efficiency, and a massive number of users. NOMA allocates entire resource blocks while providing maximum power to the weakest user [121].

4.14. Massive MIMO

Considering the great amounts of capacity dropped in older generations due to the sharing of time or frequency resources in TDMA and FDMA schemes, a solution where all resources are available for each user without interfering with others should be established. This will lead to a drastic increase in spectral efficiency and throughput. Beamforming is a substantial solution for overcoming capacity problems where a base station has multiple antennae with high directionality. Each antenna precisely focuses on a narrow area so that users who have a connection with another antenna can also use the same frequency band independently of time, thereby contributing to high data rates. Beamforming also has other advantages. At higher frequencies, since antennae in MIMO systems have large gains in one direction, the signal can be transmitted at longer distances to mitigate the attenuation problem. More signal power is delivered to the user as compared to the single antenna situation of old technologies. Another benefit of beamforming is the degradation of intercellular interference due to the directionality of the antennae.

MIMO technology has been utilized in 4G with only 8 antennae. It was then enhanced to 256–1,024 antennae in 5G. Massive MIMO has a critical role in new communication systems since it is capable of increasing system capacity by means of spatial multiplexing and reducing path loss by utilizing beamforming. It is expected that 6G will set up more than 10,000 antenna elements with super-narrow beams, leading to high spectrum efficiency and reduced propagation loss for high-frequency signals [25].

4.15. Blockchain technology

The data in blockchain technology is in cryptographically-protected distributed blocks attached to each other. Blockchain can be used to manage and organize large amounts of data as well as massive networking in the 6G network. It can also be applied to spectrum sharing, enabling users to apply the same spectrum, thus addressing the issue of large spectrum requirements in 6G and ensuring reliable, low-cost, smart, and effective spectrum usage [122]. Integrating blockchain with AI and applying deep reinforcement learning to the network will boost QoS by facilitating smart resource sharing, an advanced caching system, and a more scalable network [123]. Low delay is essential for blockchain technology since it is used in huge data organizations. This near-zero delay requirement can be met by the 6G mobile technology instead of the current 5G technology. In blockchain technology, the network infrastructure must accommodate the massive volume of real-time transactions produced by future systems. These aforementioned requirements are essential for blockchain technology and can be met with 6G technology [94,124]. Fig. 12 represents the advantages of 6G on blockchain technology.

Blockchain has had a revolutionary impact on huge industries like banking and finance. It provides a trustable and transparent business for individuals in a network [125]. Blockchain can be advantageous for the telecommunication industry. One aspect is internal network operations. By means of smart contracts, transactions can be performed using several computer codes without unnecessary traffic, thereby reducing significant resources and network bandwidth [115].

4.16. Tactile internet

Interaction between smart devices has been established with the development of IoT. The next step is called "Tactile Internet," where H2M interactions are performed in real-time with the help of haptic sensors [115]. This communication enables people to remotely sense and control devices. One of the main challenges of the haptic internet is creating pressure on the skin without any physical object. One way to produce this sense of touch is with intense pressure sound waves. The Tactile Internet can be useful in military applications because the sense of touch increases awareness of the environment and allows for faster reaction times with a low-latency system [126].

4.17. Quantum communication & quantum ML

The increasing demand for fast, reliable, intelligent, and secure communication has triggered the necessity for high computational power, which can be accomplished with 6G. Quantum computing (QC) can satisfy expectations since multi-dimensional large-sized data can be processed in parallel. QC goes beyond the traditional computing technologies. Some algorithms with advanced link capacity, such as successive interference cancellation (SIC), a have long operation time. QC can be performed with key algorithms in a much shorter time [5].

5. Challenges and research directions

The world has already adopted the 4G standards and has decided they are not sufficient for numerous applications. 5G will be the first step towards truly establishing fast and reliable internet access. Although 5G is a big step, it is only the start. 6G, considered as a more advanced version of 5G, will offer the world a new internet era. 6G will transform our lives into ones that may resemble science fiction movies. In the section, we briefly provide a discussion of challenges and future research directions related to the 6G network.

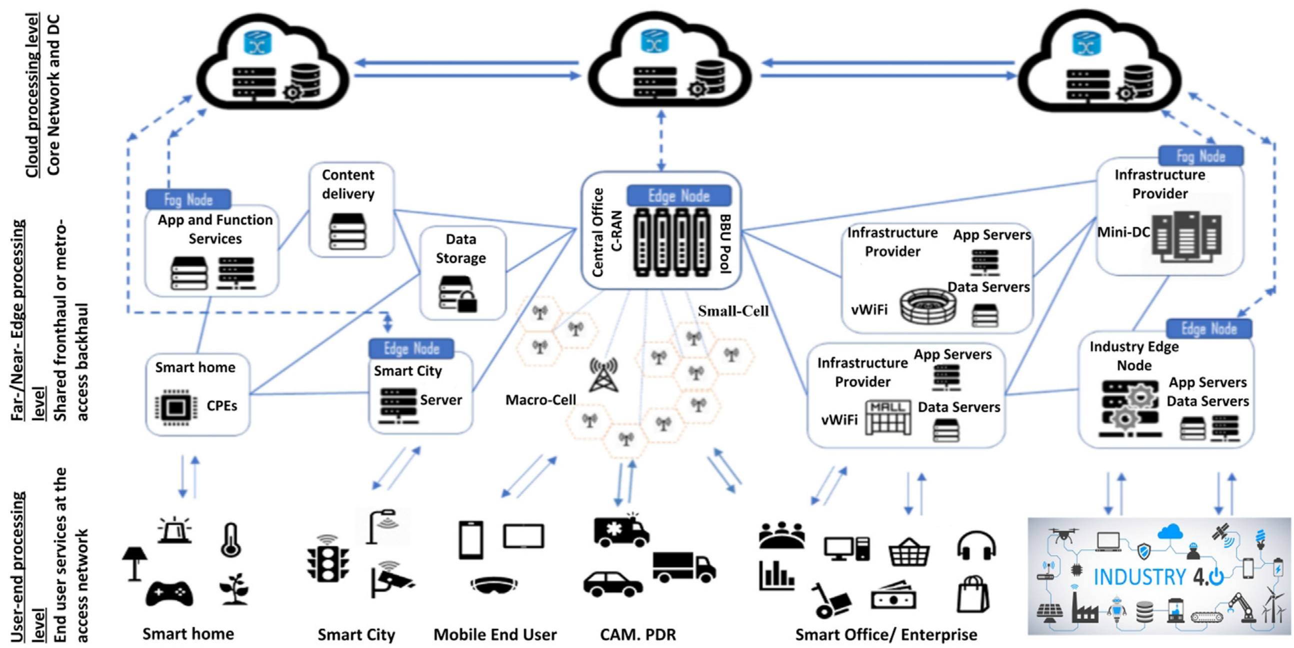

Fig. 13 Entire network structure.

5.1. Sustainability and green

Various societies, such as the United Nations and European Union, are known as the regulatory groups for revolutionary technology. Due to the global and climatic changes of the 21st century, countries now aim for more sustainable technological developments. There are concerns that 6G technology will further contribute to raising the carbon footprint since it will increase antenna placement or the number of IoT devices. However, similar to intermittent signal technology in 5G, enormous energy savings can be accomplished in 6G. The effective use of 6G technology in health, agriculture, entertainment, and several different areas will end activities that create substantial carbon emissions in everyday life. With such advantages and disadvantages, some challenges will emerge in the advancement of this technology [127,128].

5.2. Trustworthiness –security

Security has become a crucial issue in all fields where significant efforts are continuously made [129,130]. New devices and usage patterns have emerged with technological developments, giving rise to many different vulnerabilities. The existence of these vulnerabilities can be maliciously exploited. The increase in the use of IoT devices with additional technologies, such as MEC, may widen the security gaps to an incredible level. For this reason, confidence in new developments always begins at very low levels. With an even more obscure technology, such as 6G, trust issues will arise. This can be defined as a significant challenge that must be overcome.

5.3. Coverage

Coverage area is another challenge that requires attention. The goal of 6G is to develop a network that can cover the entire world and even space. This service should reach populated areas as well as extreme points where devices are present. Access to this technology should be provided in various environments, such as land, sea, and even space. In this way, an integrated digital world can be imagined. Digital media only seems possible in this respect. This situation will definitely raise other challenges,such as economic issues [40].

5.4. Applications and performance

If the 5G technology continues its current success, it will spread to the farthest points among populations, allowing experience to reach high levels. However, more will be desired. Therefore, a few steps must be considered. 6G technology will come into play with several advantages thanks to various features such as near-zero latency, long range capability, and reduced power consumption. The 5G to 6G conversion will be realized when the demand reaches extremely high levels. These technologies, which can be used in all areas of life, will definitely be employed in several critical fields that require high performance. An example would be Extremum Reality. The capability to continue real-time meetings and operations from a distance in areas such as medicine, defense, or space will become possible. For instance, more sterile brain surgery from afar can be made possible. Such extreme applications may pose new challenges for this technology [55].

5.5. Integrating systems

With developing technology, numerous automated system requirements have surfaced, driven by ML and AI. However, much work is currently needed to establish flawless systems. A glitch that may occur in critical real-time jobs can be expensive. Both ML and AI technologies must be adequately developed using 5G and 6G infrastructures as suitable platforms to function at an optimum level. Currently, all owned devices have gained the title of "smart device" with these developments [49]. A considerable challenge will be defining the most efficient integration of these devices and infrastructure, as shown in Fig. 13.

5.6. New core network architecture

Previously, terrestrial mobile systems and satellite mobile systems were separate entities with two-dimensional network architectures. In terms of technology, 6G will combine terrestrial wireless mobile communication, medium and low orbit satellite mobile communication, and short-distance direct communication. Simultaneously, 6G will incorporate communication, computing, navigation, perception, and other new technologies. By effectively utilizing intelligent mobility management and control strategies, 6G will establish a new 3D core network architecture capable of integrating terrestrial and satellite mobile systems. It will enable global ubiquitous coverage of high-speed mobile communications, including those in the air, space, on earth, and at sea [17].

However, this 3D core network architecture has the potential to overcome conventional coverage restrictions and eventually create unprecedented universal coverage. The following challenges must be overcome before it can be made available.

5.6.1. New three-dimensional core network

The 6G core network will be a 3D network made up of network nodes from a terrestrial system and network nodes from a satellite system. By incorporating some network functions into the satellite, a satellite node will become a part of a serving core network. The 6G network is a service-driven intelligent network that can dynamically allocate network resources based on service requirements and user priorities.

5.6.2. Intelligent mobility management

The mobility management of 5G and pre-5G networks did not consider network node movement. The fast-moving satellites will create major challenges to 6G. The 6G mobility scenarios will be much more complex. The inter-satellite links change as the satellite position changes. The relocation will have an effect on network topology, handover control techniques, and so on.

5.6.3. Efficient network resource utilization

Multi-dimensional information must be processed effectively based on global coverage and overall collaboration capability. Wireless resources must be assigned uniformly and effectively, and various networks must be controlled and managed on demand. However, terrestrial networks and satellite networks have different architectures and reliability in different scenarios. The service-driven, intelligent, and 3D core network will hide dynamic change between terrestrial and satellite networks behind data transmission.

5.6.4. Protocol interoperability

The TCP/IP protocol is commonly used in terrestrial networks. Because the communication channel in satellite networks has an ultra-wide bandwidth, a long transmission delay, and a higher bit error rate, the traditional protocol will be inefficient due to its initial design for computer networks only. As a result, different protocols must be interoperable in order to ensure seamless transfer between terrestrial and satellite networks.

5.7. Economic prospect

Today, the most important issue that must be addressed (other than technical issues from the aspect of engineering) is economic factors [131]. A global technological revolution such as 6G can be defined as a high-scale, costly business. The most important limitation for any project would be economic restrictions. A very precise calculation must be made in this regard. The project should progress according to these calculations, otherwise the expected efficiency may be far from what was planned. The optimization of this situation can be defined as a very significant challenge. Patwary et al. [132] emphasized key points in reducing cost. 6G technology, which similarly functions as 5G, can be cost efficient if integrated with the 5G infrastructure. Making neutral hosting and location-based spectrum licensing is thought to reduce the total cost by 50 %.

5.8. Standardization

Standardization is a critical factor. The ETSI is involved in the standardization of the telecommunications field. All regulations, from frequency ranges to antenna parameters, are incredibly critical. It has become relatively difficult to keep up with the technological developments of recent years. 6G technology is already being discussed before 5G technology has even reached global levels. Insufficient experience will cause parameters to be determined differently. This situation may lead to uncertainty in the telecommunication sector. Therefore, standardization is a serious challenge in the face of these developments.

5.9. Device capability

Devices are further evolving and developing with the new technology. Developments in the field of telecommunications have led to 5G compatible devices. In a constantly evolving environment, the adaptation of smart devices to new technologies is crucial. The incompatibility of 5G smart devices with 6G will incur an enormous economic cost, making the capability and integration of devices extremely important. The ability to harmoniously combine two new yet different technologies into a single device can be seen as another challenge in light of these developments [39].

5.10. Management

Although it is a highly technical issue, management and operational aspects are tremendously vital. Legal regulation and management between the country and the operator, between the operator and the user, and between the operator and the infrastructure provider are also significant development challenges [72]. A highly professional team must be selected. The team must have full command of all matters, from legal and country regulations to technical infrastructure and privacy of

Table 6 Summary of general challenges in 6G.

Challenges	Restrictions/Relevant research questions
Sustainability and green	There are numerous challenges that must be investigated and addressed in order to achieve a potentially sustainable network, such as: • Green communication requires advanced power transfer and energy harvesting techniques from heterogeneous devices. • Ensure network sustainability for users with varying levels of processing power. • Ensure that Super Energy efficient algorithms are used for a large number of devices. • Ensure advanced 6G system provides reconfigurable intelligent surfaces for sustainable communication.
Trustworthiness – security	The deployment of security, privacy, and trust measures is challenging due to the massive scale of 6G networks, applications, and services. Several questions are listed as follows and need to be addressed. • How to implement security and privacy measures in the undefined 6G architecture? • When new network elements can be instantiated on-demand in 6G applications, how should authentications be performed? • What security and privacy issues are associated with such technologies that have not yet been fully expected or identified? Another issue is what happens when AI-based tools are used to launch attacks? • How to design and build a privacy-enabled AI model that protects users' privacy while making their data as useful as possible?
Coverage	Some interesting research questions that must be addressed in order to achieve the 6G vision of extreme global coverage: • How to smartly handle smooth 3D navigation while moving vertically up (in air or space) or down the ground level? • How can power radiation and system efficiency be improved while obtaining global coverage? • How to create an automated, open, and decentralized wireless sector that encourages entrepreneurs to take part in order to achieve global coverage?
Applications and performance	The key restrictions and related research questions that must be clarified in order to achieve the ultimate mobile experience originally envisioned with 6G are as follows. • How can Tbps data rates be provided to enable FeMBB, extreme availability and reliability in the 99.99999 percent range, and ultra-low latency of less than 1 ms? • How can neighboring devices work together to have a powerful edge intelligence operation with <10 ns latency issues? • How can sensors and interfaces be integrated into the environment to deliver smooth gadget-free interaction? • How to connect and handover data from up to 1 million connected devices/km2? • What is the best way to ensure a high customer satisfaction in services such as holographic telepresence (HT) and XR?
Integrating systems	For hyper-intelligent networking in 6G, several obstacles and research questions must be overcome. • How to make standard and high-quality data sources for active learning in networks with varying characteristics (for example, cognitive radio technologies, channel modeling, and densification level)? • How can hybrid centralized-distributed AI solutions be provided to leverage the effective computing capabilities of centralized cloud servers along with the computing resources available at massive IoT devices at the edge of the network? • How can AI solutions be used to empower networks to be fully programmable in order to support flexible and software-based 6G system implementation? • How to build predictive orchestration strategies to support a few billion IoT devices, zero-latency services, and extremely high capacity.
Device capability	• Some 6G features may not be supported by 5G devices, and the cost of 6G devices may rise as their capabilities improve. Another challenge in light of these developments is How to harmoniously combine two new yet different technologies into a single device?
Enabling satellites	• How to effectively control and manage a swarm of LEO and VLEO satellites while also enabling them to communicate in a secure and cost-effective manner? • What are the time-efficient solutions that can help mitigate the Doppler shift and Doppler variation challenges caused by the relative movement of the earth and LEO satellite? • How to deal with the receiver sensitivity, signal detection quality, and receiving performance challenges associated to Transmission Technology for Inter-Satellite Link (ISL)?

personal data. Since it will be a global technology, managing relations with other countries is another significant issue.

5.11. Enabling satellites

6G will extensively use satellites for internet connections. Emerging technology have already enabled satellites for internet connection. 6G will further adapt this technology to provide a reliable, robust, and low-latency internet connection. However, one major issue will be the doppler shift. The doppler shift is the change of a wave's frequency with respect to an observer who is moving relative to the wave's origin [133]. The Doppler effect will be an issue when low earth orbital satellites attempt to communicate with geostationary satellites since low earth orbital satellites move extremely fast. Geostationary satellites stand still with respect to the earth, further causing communication issues. As established in [17], an orbital satellite at a height of 600 km will experience the doppler effect, which occurs at 480KHz in the Ka-band of a 20 GHz carrier. This will disturb communication in various ways. The second challenge is the large delay times in transmission. Satellites are located far away from the ground, making transmission distances much longer than conventional systems. As stated in [17], the low earth orbital signal transmission delay is huge in contrast to terrestrial systems. Greater distance also means greater path loss. As stated in [134], path loss is the reduction in the power density of an electromagnetic wave as it propagates through space. It is inversely related to the distance between the transmitter and receiver. The attenuation factor will also be much higher than conventional systems since satellites have large path loss and transmission delays. Since the integrated satellite and terrestrial networks have different properties, designing a network architecture to form a unified management will be a problem, as published in [135]. End users must have a smooth changing connection method between satellite and terrestrial connections, 6G, and 5G without experiencing any connection problems. Routing among inter-satellite links will be another issue. When the number of earth stations is not enough, satellites must transfer data between themselves to reach the end user from the earth station. Since this hop is dynamic, designing the routing algorithm to optimize the time cost and reduce the power spent will be challenging, as published in [135].

5.12. Peak data rates

The 6G technology must utilize extremely high frequency (EHF) bands to increase its capacity. Electromagnetic waves in the EHF bands are exposed to large path losses, which is why the communication range is very short. This will enable extensive frequency reuse. An enormous number of access points are required to use this ability, which is a great economic drawback. These access points will create an extremely dense wireless network, creating the problem of handovers, as mentioned in [17,34]. When the coverage area for every access point is small, mobile users will experience a high number of handovers to stay connected to the 6G network.

5.13. THz wireless communication

The THZ bands are relatively narrow compared to lower frequency bands, yet directional antennas are preferred over other types. Determining the MIMO structures for 6G remains a problem. A massive MIMO structure where every antenna focuses on a narrow THz beam will be almost impossible by today's standards [95]. THz communications have significant advantages for 6G and beyond applications, many technical challenges need to be addressed before successful deployment.

5.13.1. High-Frequency hardware components

It is difficult to design efficient radio-frequency (RF) circuits for solid-state THz communication systems, such as THz mixers, THz oscillators, THz amplifiers, and THz antennas. Specifically, designing ultra-broadband THz antennas with high gain and fast beam scanning is a significant challenge. Physically, the low noise design for such high bandwidth super-heterodyne transceivers is also a global challenge.

5.13.2. THz communication channel modelling and estimation

It is critical to establish accurate channel models for THz communications in order to implement efficient wireless communication systems in the THz band. THz channel modeling must take into account several unique factors, such as the highly frequency-selective path-loss caused by oxygen and water–vapor molecule absorption loss. For communication systems with ultra-massive antenna arrays, efficient channel estimation schemes with low computational load are thus desirable.

5.13.3. Directional networking for THz wireless communication

Although the beams of the THz band are relatively narrow when compared to lower frequency, the directional antenna is still desirable for THz communication networking because it can concentrate the THz wave energy in a specific direction to support longer-distance communication and reduce interference toward adjacent nodes. THz-band directional networking challenges include efficient neighbor-discovery algorithms in a time-asynchronous system, topology control algorithms with an optimum trade-off between node degree and jump stretch, and a multiple-access-control (MAC) protocol with higher access capacity and lower resource utilization.

To conclude, 6G will dramatically change our lives. However, it must first overcome numerous challenges. With new technology, mankind will have access to faster, more reliable, robust, low-latency internet connections from anywhere, using brand-new application fields that make life easier and safer. Table 6 summarizes several key constraints and relevant research questions in the implementation of 6G mobile networks.

6. Conclusion

This article extensively investigates the advantages and opportunities, considering recent research articles and efforts by researchers worldwide. In this article, we visualized the requirements, specifications, network architecture, usage scenarios, and current active studies regarding 6G technology. Following that, we discussed the opportunities and advantages of 6G mobile technology, including key factors and examples. We also highlighted the critical technology expected to enable the 6G system. In addition, we discussed several possible challenges to effectively implement 6G mobile networks, identifying the main challenges and future directions to accomplish the goals of 6G technology.

Based on the findings of this comprehensive study, we conclude that enabling MBRLLC and mobility management at high-frequency mmWave bands and beyond is a first step toward 6G. A paradigm shift for 6G is required from radio-centric system design (i.e., 3GPP) and toward an end-to-end convergence of communications, computing, control, localization, and sensing (3CLS) co-design orchestrated by an AI-driven intelligence substrate. The 6G vision will not be as simple as examining additional high-frequency spectrum bands to increase capacity. Conversely, it will be motivated by a variety of applications, technologies, and methods. 6G will usher in a new era of smart surfaces communicating with human-embedded implants, moving away from the smartphone-base station paradigm. Operating in 3D space and moving away from simple averaging toward fine-grained analysis that deals with tails, distributions, and quality-of-physical-experience (QoPE) are recommended for 6G performance analysis and optimization. To meet those lofty goals, AI/ML techniques will be critical components of 6G, such as automating decision-making processes and achieving a zero-touch approach. 6G mobile network promotes AI-based technologies, which are becoming increasingly important since more industries are incorporating AI into their operations. Most sectors from various areas are planning to work on projects related to 6G mobile technology due to its potential. In light of this information, it is clear that our lives will become more comfortable. When compared to current mobile communication technology, our problems will have more advanced solutions with 6G mobile technology and its key features.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. See Table 7.

Table 7 List of abbreviation.

Item	Descriptions	Item	Descriptions
3D	Three-Dimensional	MMS	Multimedia Messaging Service
AI	Artificial Intelligence	muRLLC	Massive Ultra-Reliable Low Latency Communications
B5G	Beyond 5 Generation	MBRLLC	Mobile Broadband Reliable Low Latency Communications
BCI	Brain-Computer Interference	MTC	Machine Type Communication
Bps	Bits per second	MTC	Machine Type Communication
CAVs	Connected Autonomous Vehicles	NFV	Network Function Virtualization
CR	Cognitive Radio	NLOS	Non-Line of Sight
EI	Edge Intelligence	NOMA	Non-Orthogonal Multiple Access
eMBB	Enhanced Mobile Broadband	OAM	Orbital Angular Momentum
ETSI	European Telecommunications Standards Institute	QC	Quantum Communication
eRLLC	Extremely Reliable and Low Latency Communications	QC	Quantum Computing
FDD	Frequency Division Duplexing	QML	Quantum Machine Learning
OFDMA	Orthogonal Frequency Division Multiple Access	QoS	Quality Of Service
FDMA	Frequency Division Multiple Access	RF	Radio Frequency
FeMBB	Further Enhanced Mobile Broadband	RL	Reinforcement Learning
IoBNT	Internet Of Bio Nano Things	RSRP	Reference Signal Received Power
IoE	Internet Of Everything	SDNs	Software Defined Networks
IoNT	Internet Of Nano Things	SIC	Successive Interference Cancellation
IoST	Internet Of Space Things	SMS	Short Message Service
IoST	Internet Of Space Things	SR	Symbiotic Radio
IoT	Internet Of Things	uHDD	Ultra-High Data Density
IR	Infrared	umMTC	Ultra-Massive Machine Type Communications
IRS	Intelligent Reflective Surfaces	uRLLC	Ultra-Reliable Low-Latency Communications
KPIs	Key Performance Indicators	uHEE	Ultra-High Energy Efficiency uHS Ultra-High Security
LEDs	Light Emitting Diodes	UAVs	Unmanned Aerial Vehicles
LEO	Low Earth Orbit	URLLC	Ultra-Reliable Low Latency Communications
LOS	Line Of Sight	VAR	Virtual Augmented Reality
M2M	Machine-To-Machine	VLC	Visible Light Communication
MBBLL	Mobile Wide Bandwidth and Low Latency	VR	Virtual Reality
MEC	Multi-Access Edge Computing	WET	Wireless Energy Transmission
MIMO	Multiple Input Multiple Output	WIET	Wireless Information and Energy Transmission
ML	Machine Learning	XR	Extended Reality

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