6G Networks and AI Revolution - Exploring Technologies, Applications, and Emerging Challenges

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Review

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Abstract: In the rapidly evolving landscape of wireless communication, each successive generation of networks has achieved significant technological leaps, profoundly transforming the way we connect and interact. From the analog simplicity of 1G to the digital prowess of 5G, the journey of mobile networks has been marked by constant innovation and escalating demands for faster, more reliable, and more efficient communication systems. As 5G becomes a global reality, laying the foundation for an interconnected world, the quest for even more advanced networks leads us to the threshold of the sixth-generation (6G) era. This paper presents a hierarchical exploration of 6G networks, poised at the forefront of the next revolution in mobile wireless technology. This study delves into the technological advancements that underpin the need for 6G, examining its key features, benefits, and the key enabling technologies. We dissect the intricacies of cutting-edge innovations like terahertz communication, ultra-massive MIMO, artificial intelligence (AI), machine learning, quantum communication, and re-configurable intelligent surfaces. Through a meticulous analysis, we evaluate the strengths, weaknesses, and state-of-the-art research in these areas, offering a wider view of the current progress and potential applications of 6G networks. Central to our discussion is the transformative role of AI in shaping the future of 6G networks. By integrating AI and machine learning, 6G networks are expected to offer unprecedented capabilities, from enhanced mobile broadband to groundbreaking applications in areas like smart cities and autonomous systems. This integration heralds a new era of intelligent, self-optimizing networks that promise to redefine the parameters of connectivity and digital interaction. This paper also addresses critical challenges in the deployment of 6G, from technological hurdles to regulatory concerns, providing a holistic assessment of potential barriers. By highlighting the interplay between 6G and AI technologies, this study not only maps out the current landscape but also lights the path forward in this rapidly evolving domain. This paper aims to be a cornerstone resource, providing essential insights, addressing unresolved research questions, and stimulating further investigation into the multifaceted realm of 6G networks. By highlighting the synergy between 6G and AI(Artificial Intelligence) technologies, we aim to illuminate the path forward in this rapidly evolving field.

Keywords: 6G; 5G; terahertz communication; ultra massive MIMO; artificial intelligence; machine learning; quantum communication; millimeter waves; blockchain; Internet of Things

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1. Introduction

As globalization continues to advance, the volume of mobile data traffic is experiencing a rapid and exponential increase. According to a report by the ITU-R, global mobile data traffic was 158 exabytes per month in 2022 is projected to reach to 2194 exabytes per month by 2028 and 5016 exabytes per month by 2030 [2]. These numbers represent an exponential increase in the amount of data consumed by mobile subscribers, with each subscriber projected to consume 257 gigabytes of data in 2030 compared to 12.1 gigabytes in 2022 [1]. The growing demand for mobile data services is not limited to a particular region or demographic [3]. It's anticipated that by 2025, around 70% of the

global population will utilize mobile services, with approximately 60% accessing mobile internet. This growth is further propelled by the proliferation of new technologies such as the Internet of Things, artificial intelligence, blockchain, augmented and extended reality, 3D video, and connected vehicles [5].

To meet the increasing need for mobile data services, 5G technology has been deployed worldwide [4]. However, with the world moving towards automation, it is apparent that a more advanced technology than current 5G networks will be required to handle the rising data traffic [6]. This is where the sixth generation '6G' network comes in, which is expected to provide users with high-quality service while coping with this exponential increment in data traffic [7,8]. The sixth-generation network promises to be a game-changer in mobile wireless technology, with its ultra-fast data speeds, low latency, and massive connectivity [9]. 6G networks will transform mobile networks by integrating artificial intelligence and machine learning to seamlessly combine the physical, digital, and biological worlds [10]. This integration will enable the creation of new use cases and applications that were not previously possible with 5G networks. Moreover, 6G networks will lay the foundation for developing smart cities, autonomous vehicles, and other applications that require reliable, high-bandwidth, and low-latency connectivity [11].

In this paper, we take a hierarchical approach to 6G networks and present a comprehensive overview of the 6G networks. Our summary of contributions and paper organization are as follows.

Section 2 delves into the evolutionary journey of wireless communication technologies, spanning from the inception of 1G to the cutting-edge developments of 6G. In Section 3, we explore the distinctive features that define 6G networks, shedding light on the anticipated capabilities and innovations that set it apart from its predecessors. Section 4 discusses the integration of artificial intelligence and machine learning in 6G networks. Section 5 addresses the pressing question of "When Will 6G Come Out?" by examining current timelines, ongoing research initiatives, and industry expectations surrounding the deployment of 6G technology. Section 6 investigate the diverse applications of 6G networks, envisioning the transformative impact on industries, services, and everyday life. Section 7 scrutinizes the challenges associated with the deployment of 6G, ranging from technological hurdles to regulatory considerations, providing a comprehensive assessment of potential obstacles. In Section 8, we explore the key technologies that shape the deployment of 6G network. Section 9 examines the question of whether 6G poses health risks, delving into existing research surrounding the potential dangers of advanced wireless technologies. Section 10 opens the door to future research endeavors by outlining open topics in 6G networks. Section 11 briefly touches upon the speculative realm of 7G networks, contemplating the potential directions and features that may define the next frontier in wireless communication. Finally, Section 12 draws conclusions from the comprehensive analysis, summarizing key findings and insights derived from the exploration of 6G networks and setting the stage for further research and development in the field.
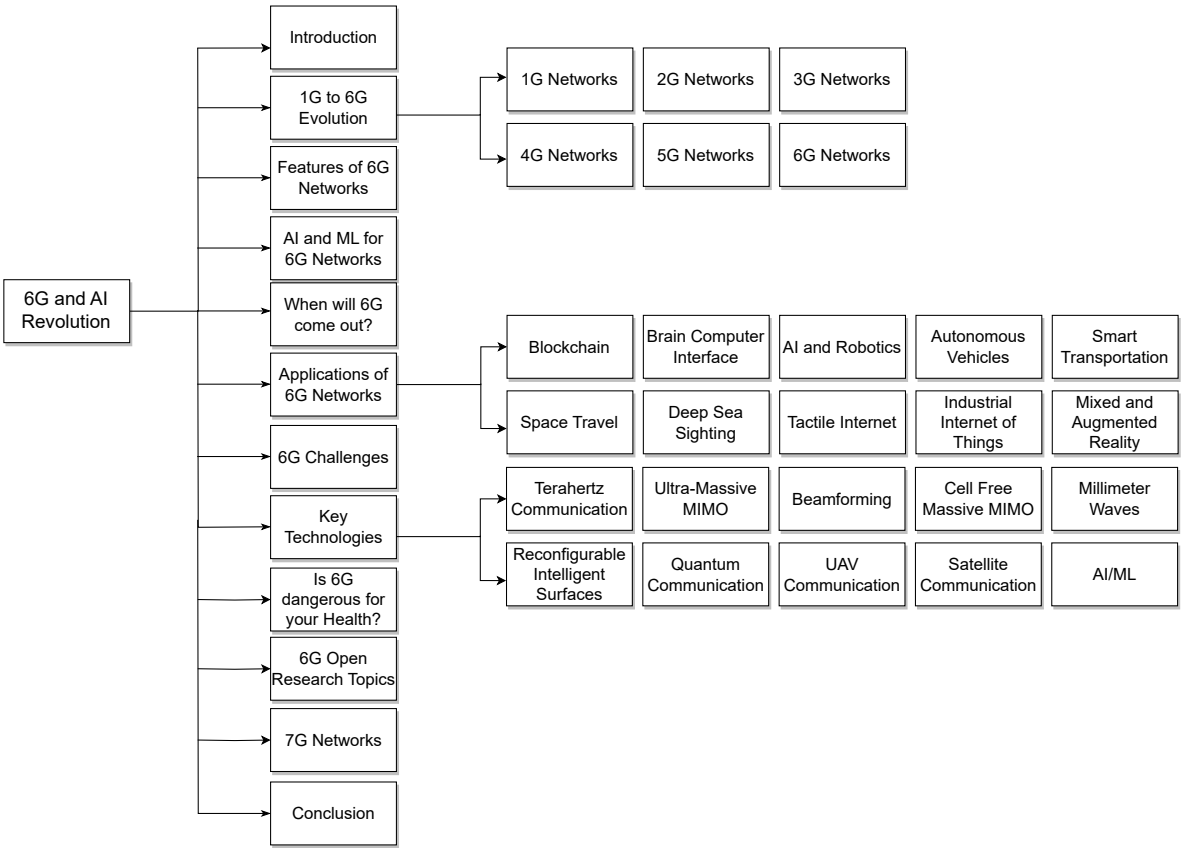
Figure 1. Organization structure of the paper .

2. Evolution from 1G to 6G Networks

The era of mobile communication started in the early 1980s and has seen significant development and expansion in the decades that followed [12]. The advancement of mobile wireless technology can be divided into distinct eras, each of which has brought about substantial progress and developments in data rates, connectivity, and functionality.

2.1. 1G

The initial phase of mobile wireless technology, referred to as 1G, was introduced in the early 1980s and was primarily based on analog technology [13]. This generation of technology was primarily utilized for voice communication and was distinguished by its low data transfer speeds and subpar audio quality [14]. Some examples of 1G include Advanced Mobile Phone System (AMPS), Total Access Communication System(TACS), and Nordic Mobile Telephone(NMT) [15].

2.2. 2G

The introduction of second-generation (2G) mobile networks in the early 1990s marked a shift from analog to digital technology [16]. Along with traditional voice services, 2G networks introduced new capabilities such as Short Message Service (SMS) and basic email functionality. 2G networks also brought improvements in audio quality and enhanced security [17]. Some of the well-known 2G (Second Generation) mobile networks include GSM (Global System for Mobile Communications), IS-95 (Interim Standard-95), PDC (Personal Digital Cellular), and CDMAone (Code Division Multiple Access).

2.3. 3G

The introduction of 3G (Third Generation) mobile networks in the early 2000s marked a significant advancement in mobile technology, providing both voice and data services [18]. These networks offered elevated data transfer speeds and the capability of web browsing on mobile devices [19]. They also introduced Multimedia Message Support (MMS) and the ability to use data-intensive applications such as email, web browsing, video streaming, and mobile television [20]. In addition to providing enhanced data transfer speeds and web browsing capabilities, 3G networks expanded the coverage area and incorporated security measures such as packet data confidentiality and integrity. Some examples of 3G (Third Generation) mobile networks include CDMA2000 (Code Division Multiple Access 2000), WCDMA (Wideband Code Division Multiple Access), and EDGE (Enhanced Data rates for GSM Evolution) [21].

2.4. 4G

The introduction of 4G (Fourth Generation) mobile networks in the early 2010s marked a significant advancement in mobile technology, offering high data transfer speeds and improved network coverage [22]. These networks enabled HD video streaming, mobile video conferencing, online gaming, and high-speed mobile Internet. Examples of 4G (Fourth Generation) mobile networks include LTE (Long-Term Evolution) and WiMAX (Worldwide Interoperability for Microwave Access) [23].

2.5. 5G

The introduction of 5G (Fifth Generation) mobile networks in the early 2010s represents the latest advancement in mobile technology, with the first 5G mobile towers coming online in 2018 [24]. These networks are distinguished by extremely high data transfer speeds, improved network coverage, and ultra-low latency. 5G networks are expected to be a foundation for the Internet of things (IoT), smart cities, and the fourth industrial revolution [25].

2.6. 6G

networks are currently being researched and developed as the next evolution of mobile networks, with the expectation of providing unparalleled transmission speeds, ultra-low latency, and improved coverage [26]. These networks will incorporate cutting-edge technologies such as terahertz communication, ultra massive MIMO, artificial intelligence, machine learning, quantum communication, millimeter, reconfigurable intelligent surfaces [27] etc. Potential applications for 6G networks include Linked robotic and self-governing systems, wireless brain-computer interfaces, blockchain advancements, immersive multi-sensory realities, space and deep-sea exploration, tactile internet capabilities, and industrial networking.
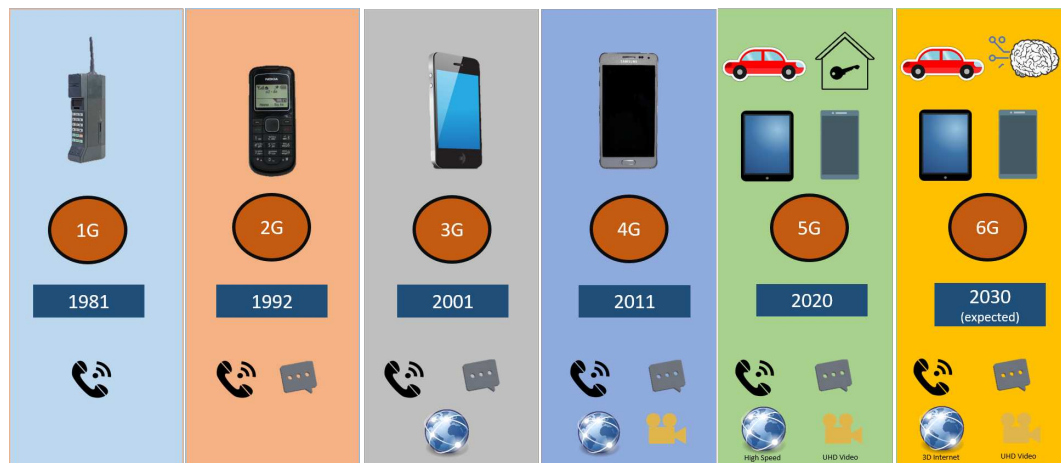
Figure 2. Evolution of Mobile Communications - A chronological depiction of the advancements in mobile network technology from 1G in 1981 to the expected 6G in 2030. This visual encapsulates the major milestones in mobile communications, including the emergence of 2G and the introduction of SMS in 1992, the advent of 3G and mobile data in 2001, the expansion to 4G and high-speed internet access in 2011, and the integration of IoT with 5G in 2020. The future projection of 6G suggests a paradigm shift to smarter, AI-driven networks supporting 3D internet and enhanced video capabilities .

3. Features of 6G

6G networks are expected to bring significant advancements over the current 5G technology. The features and advantages of 6G networks are summarized in Figure 3. Here are some of the key features and potential advancements associated with 6G:

- **High data transfer rates**: 6G networks are expected to bring tremendous advancements in terms of data transfer speeds, with the potential to reach up to 10 Tbps. This represents a significant increase when compared to the current data transfer speed set for 5G networks, which is 10 Gbps [36].
- **Low latency:** 6G networks are expected to provide ultra-low latency, potentially reaching as low as 0.1 ms, which is a significant improvement over the latency of 5G networks with latency requirement of 1 ms [37].
- **Extended coverage:** 6G networks are expected to have an extended coverage range, potentially reaching deep-sea, space, and underground areas. This would enable the use of new applications such as deep-sea sightseeing, space travel, and industrial internet [38].
- **Enhanced user experience:** 6G networks are projected to enhance the user experience by amplifying the capabilities of extended reality, augmented reality, virtual reality, and artificial intelligence [39].
- **Increased spectral efficiency:** 6G networks are expected to offer spectral and network efficiency ten times greater than that of 5G networks [40].
- **Ubiquitous connection:** 6G networks are expected to provide enormous broadcasting data and support more than 1 million connections, which is a hundred times more than current 5G networks [41].
- **Better energy efficiency:** 6G networks are expected to have an optimized energy consumption, resulting in longer battery life, making it more sustainable and efficient to use [42].
- **Integration with other technology:** Anticipated integration of 6G networks involves seamless incorporation with other technologies such as the likes of IoT, cloud computing, and big data analytics, ensuring efficient connections across various systems [43].
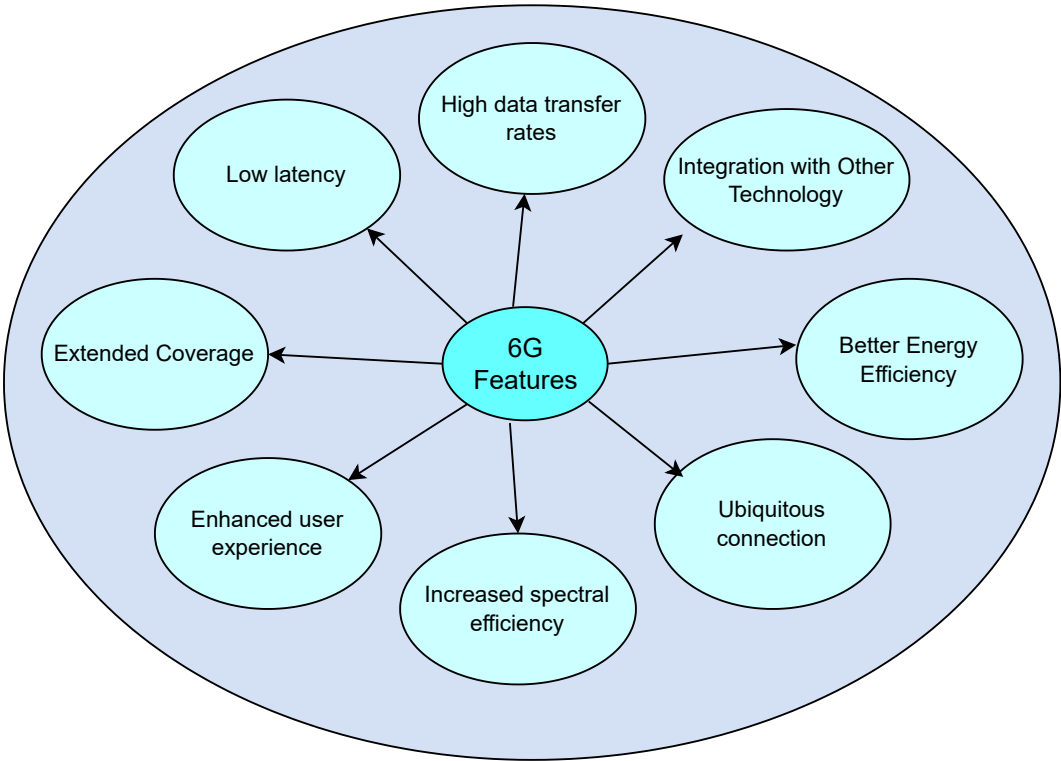
Figure 3. Features of 6G Network .

Table 1 shows the performance comparison of 4G, 5G, and 6G Networks [28,35].

Table 1. Comparison of 4G, 5G, and 6G performance indicators.

Performance Indicator	4G	5G	6G
Maximum Data Transfer Rate	100 Mbps	10 Gbps	Up to 10 Tbps
Minimum Latency	10 ms	1 ms	Up to 0.1 ms
Maximum Device Density per sq km	0.1 million devices	1 million devices	10 million devices
Energy Efficiency	1x	100x more efficient than 4G	100x more efficient than 5G
Spectral Efficiency	1x	100x more efficient than 4G	100x more efficient than 5G
Available Spectrum	Up to 6 GHz	Up to 300 GHz	Up to 3 THz
Maximum Mobility	200 km/h	300 km/h	600 km/h
Artificial Intelligence Integration	None	Partial	Full

4. Artificial Intelligence and Machine Learning for 6G Networks

AI and ML are anticipated to have a revolutionary impact on 6G networks, improving network management optimization and enhancing the user experience across various aspects. AI is expected to play a crucial role in the development of 6G networks by addressing the primary challenge of managing the significant increase in connected devices and data traffic [94]. By optimizing network resources like bandwidth and computing power, AI can guarantee the efficient operation of the network [95]. AI can enable real-time decision-making capabilities, which are essential for applications like autonomous vehicles and augmented reality to operate safely and efficiently. Furthermore, AI can create intelligent networks that can self-learn and adapt in real-time by analyzing data to improve performance and efficiency [96]. It can predict potential issues by analyzing data from sensors and other sources, preventing service disruptions. This predictive maintenance for 6G networks reduces downtime and increases reliability [97]. On the other hand, ML algorithms can analyze user behavior patterns and preferences to personalize the network experience. This includes adaptive content delivery, predictive

caching, and personalized service recommendations [**?**]. AI-driven cybersecurity measures can continuously analyze network traffic patterns, detect anomalies, and proactively respond to security threats [99]. ML models can evolve and adapt to new cyber threats, enhancing overall network security [100]. AI can also be applied to cognitive radio systems, allowing networks to autonomously adapt to changing radio conditions, interference, and spectrum availability [101]. This enables more flexible and intelligent use of available radio resources [102].Moreover, AI-driven techniques can enhance the resilience of 6G networks by predicting and mitigating the impact of faults or disruptions. ML models can adaptively reroute traffic and optimize network performance during failures [103].

ML will play a crucial role in enabling the development of 6G networks by providing intelligent and adaptive capabilities that can support various applications and services [104]. These algorithms can be employed to dynamically manage and optimize network resources in real-time depending on the network's specific use case and requirements. Reinforcement Learning (RL) algorithms, such as Q-learning and Deep Q Network (DQN), can make sequential decisions in dynamic environments. In network management, RL can be applied to optimize resource allocation, routing, and scheduling based on changing conditions [105]. Multi-objective-based genetic algorithm is an optimization algorithm inspired by natural selection which can be used to solve resource allocation problems in networks, adapting to changing demands and constraints [106]. Particle Swarm Optimization (PSO) is a population-based optimization algorithm that models the social behavior of particles. It can be employed for dynamic resource allocation, load balancing, and network optimization [107]. Deep learning models like neural networks can undergo training to forecast network performance, recognize patterns, and enhance resource allocation [108]. Deep reinforcement learning (DRL) combines deep learning with RL for complex decision-making. Fuzzy logic can be applied to model and control network parameters in a dynamic environment. It provides a way to handle uncertainty and imprecise information in network optimization [109]. Markov Decision Processes (MDP) are used in RL to model decision-making problems with sequential interactions. In network optimization, MDPs can represent the dynamic nature of resource allocation and routing decisions [110]. Swarm Intelligence Algorithms inspired by swarm intelligence, such as the Bee Algorithm or the Firefly Algorithm, can be applied to optimize network resources collaboratively [111].

5. When Will 6G Come Out?

Anticipations suggest that 6G networks could debut around 2030, potentially emerging earlier in specific global regions. 6G wireless technology is currently the focus of research and development by several countries, universities, and tech companies worldwide. China has set an ambitious goal of dominating the 6G industry by 2030, and companies like Huawei, ZTE, and China Mobile are actively involved in 6G research [44–47]. In South Korea, LG has established a 6G research center [48], while Finland's University of Oulu is leading 6G research with the country's "6G Flagship" program [49]. The US Federal Communications Commission (FCC) has opened the "terahertz wave" for experiments on next-generation standards, which could include 6G. At the same time, companies like Qualcomm and Intel are also involved in 6G research [50]. Japan's 6G research program focuses on developing technology fo r super-fast data transfer rates, and the EU's Horizon 2020 5G-DRIVE project explores the potential of 6G [51,52]. However, despite the significant efforts being made, 6G technology is still in its early stages of development, and it may be some time before 6G networks become a reality.

6. Applications of 6G Network

6G network is not yet commercially available, however, it is expected to have the applications in several domains [53]. Figure 4 below shows the Applications of 6G Network.
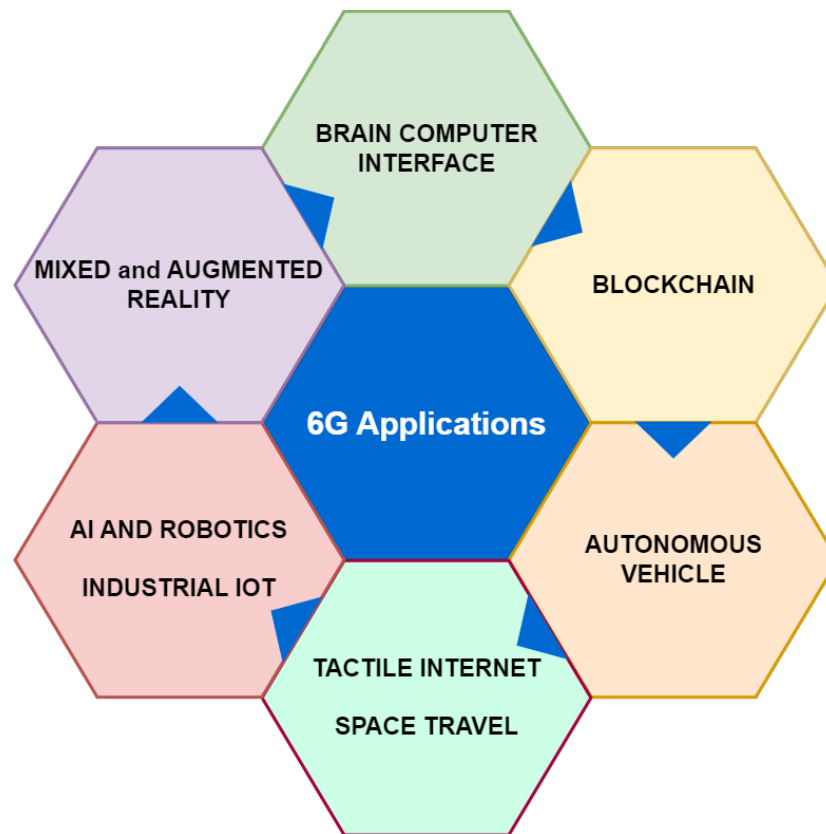
Figure 4. Applications of 6G Networks .

6.1. Brain-Computer Interfaces

Brain-computer interfaces (BCIs) aim to establish a direct link between the brain and a computer, enabling individuals to manipulate machines through their thoughts [54]. Unlike traditional input devices, such as a mouse or keyboard, a BCI decodes and interprets brain signals and converts them into control commands that the computer can execute. The objective of BCIs is to empower individuals to control machines with their thoughts alone, for instance, to operate a prosthetic limb or a wheelchair.

With the emergence of 6G, BCIs could potentially benefit from advancements in communication technologies [55]. 6G networks are projected to offer higher data transfer rates and shorter latencies, making it possible to process brain signals in real-time. This is crucial for the efficacy of BCIs, as real-time processing and analysis of brain signals are vital. The new technologies, such as terahertz communication and edge computing, available with 6G have the potential to lead to the creation of advanced, compact BCI devices with improved precision and reliability. Furthermore, integrating BCIs with other cutting-edge technologies, such as IoT and AI, could offer new avenues for developing BCI applications, including context-aware and personalized BCI-based solutions. It is essential to note that, although 6G holds excellent promise for BCIs, much research and development is still required to realize these possibilities fully.

6.2. Blockchain

Blockchain is a system that allows for the secure and transparent recording of digital transactions in a decentralized manner [56]. Integrating 6G networks with blockchain technology offers a range of benefits and potential applications. 6G, with its projected enhancements in data transfer rates, lower latency, and increased network capacity, could support the real-time processing of complex transactions and applications.

One potential use of blockchain technology in 6G is to improve security and privacy in communication and transactions [57]. The increased speed and capacity of 6G networks may enable the

implementation of blockchain-based solutions to enhance data security and protect against cyberattacks and data breaches. Another application is the development of decentralized platforms and networks by integrating blockchain technology with 6G. 6G's enhanced speed and capacity could support the creation of decentralized networks that securely store and manage large amounts of sensitive data, such as financial transactions or medical records. These decentralized systems may offer improved security and privacy compared to centralized systems and could drive the development of new services and applications [58]. Although 6G is still in its early stages of development, the potential applications of blockchain technology in 6G are vast and have the potential to significantly change the way we communicate, store, and manage data.

6.3. Space Travel

Space exploration is an area that could greatly benefit from the advancements in 6G technology. With its improved speed and capacity, 6G could facilitate real-time communication between spacecraft and ground control, streamlining missions and enabling agile decision-making [59]. The fast data transfer speeds offered by 6G enable the effective transfer of substantial volumes of remote sensing data, leading to more accurate and detailed information and the potential for new scientific discoveries. Furthermore, the strong and secure communication networks enabled by 6G could connect spacecraft and ground control, ensuring reliable and uninterrupted communication. Additionally, 6G's enhanced network capacity and low latency could support the transmission of high-resolution virtual and augmented reality data, offering an improved immersive experience for those involved in space exploration [60].

6.4. Deep Sea Sightseeing

Applying 6G in deep sea sightseeing can enhance the underwater experience for individuals. With 6G's increased data transfer rates and reduced latency, real-time communication between the deep sea and the surface could be established [61]. This could allow for transmitting high-quality images, videos, and data from the ocean's depths in real-time, providing a more immersive experience for deep sea observers. Additionally, 6G's improved network capacity and increased speed could support the deployment of underwater drones and other autonomous vehicles for deep-sea exploration [62]. These vehicles could be equipped with high-resolution cameras and other sensing devices to collect and transmit data, enabling the collection of more accurate and detailed information about the deep sea environment. The implementation of 6G in deep sea sightseeing holds great promise, but much research and development work is still needed to realize its full potential.

6.5. Tactile Internet

The tactile internet is an emerging field that seeks to create a new form of human-machine interaction through the sense of touch [63]. Applying 6G technology to the tactile internet could significantly enhance its capabilities and potential applications. 6G makes it possible for real-time, high-fidelity transmission of touch-based data. With 6G, it may be possible to create more advanced and responsive haptic systems that can provide a realistic simulation of touch, allowing for remote control and manipulation of objects, including virtual and augmented reality applications. 6G could also provide the high-speed and low-latency connectivity required to support the real-time teleoperation of robots and other remote-controlled devices, allowing for more precise and effective control[64]. Additionally, 6G's advanced communication technologies, such as edge computing and terahertz communication, may enable the development of compact and highly accurate haptic devices [65]. Integrating 6G technology into the tactile internet could open up new possibilities for human-machine interaction and have far-reaching implications for healthcare, gaming, and manufacturing industries.

6.6. Industrial Internet of Thing

The combination of 6G and the potential for transformation lies within the Industrial Internet of Things (IIoT) industrial operations [66]. 6G's real-time communication capabilities can result in more agile and efficient processes. Additionally, 6G's high data processing speeds can lead to improved decision-making and increased accuracy in industrial processes. 6G's advanced security features can better protect against cyber threats and data breaches in industrial settings. Integrating 6G and IIoT can also open the door to new IoT-based solutions, such as predictive maintenance and remote control of industrial systems [67]. With its ability to drive the creation of intelligent and automated industrial systems, 6G has the potential to increase productivity and efficiency and lower costs.

6.7. Mixed and Augmented Reality

6G technology presents an incredible opportunity to enhance mixed and augmented reality (MAR) experiences. 6G's real-time capabilities enable the seamless merging of virtual and physical realms, providing users with a more immersive and interactive experience. [68]. The transmission of high-resolution virtual and augmented reality data enabled by 6G can provide improved visual and sensory experiences in MAR applications. This opens up new possibilities for education, entertainment, and product visualization. Additionally, 6G's ability to connect individuals in virtual environments can lead to new ways for remote work, social interaction, and gaming. 6G's enhanced network security measures can provide peace of mind, protecting sensitive information and user data from cyber threats[69]. The merging of 6G and MAR technology has significant potential to generate inventive and immersive experiences, establishing it as a primary application of 6G technology.

6.8. Artificial Intelligence and Robotics

The application of 6G on AI and robotics is expected to be significant and impactful due to the increased capabilities and improved connectivity of 6G networks [70]. With 6G, AI algorithms will see a boost in accuracy and speed, while autonomous robots and drones will be equipped with real-time communication and control features. Advanced AI-powered systems, such as self-driving vehicles, smart factories, and intelligent homes, will become more sophisticated. With increased natural language processing abilities and a more comprehensive range of applications, virtual assistants will also improve. 6G will enable remote control and monitoring of AI and robotic systems in hazardous environments, and AI will be used for predictive maintenance and monitoring in industrial settings [71]. The increased connectivity and capabilities of 6G networks will also drive the creation of new and innovative AI-powered applications and services.

6.9. Autonomous Vehicles and Smart Transportation Systems

The application of 6G technology in autonomous vehicles and smart transportation systems is poised to bring significant advancements and improvements [72]. 6G networks will offer the vital infrastructure for the secure and effective functioning of autonomous vehicles, facilitating real-time communication and control among vehicles, the central traffic management system, and the surrounding infrastructure [73]. The deployment of 6G will augment the safety and dependability of autonomous vehicles through more rapid and precise decision-making. Furthermore, real-time data exchange between vehicles and infrastructure will optimize traffic management and flow, increasing efficiency and reducing congestion. The superior connectivity and features of 6G networks will foster the growth of cutting-edge smart transportation systems and services while also advancing existing autonomous vehicle technologies, such as sensors and mapping capabilities [74].

7. Challenges for 6G Deployment

The deployment of 6G technology faces numerous deployment challenges. Some of them are discussed in this section (Figure 5).
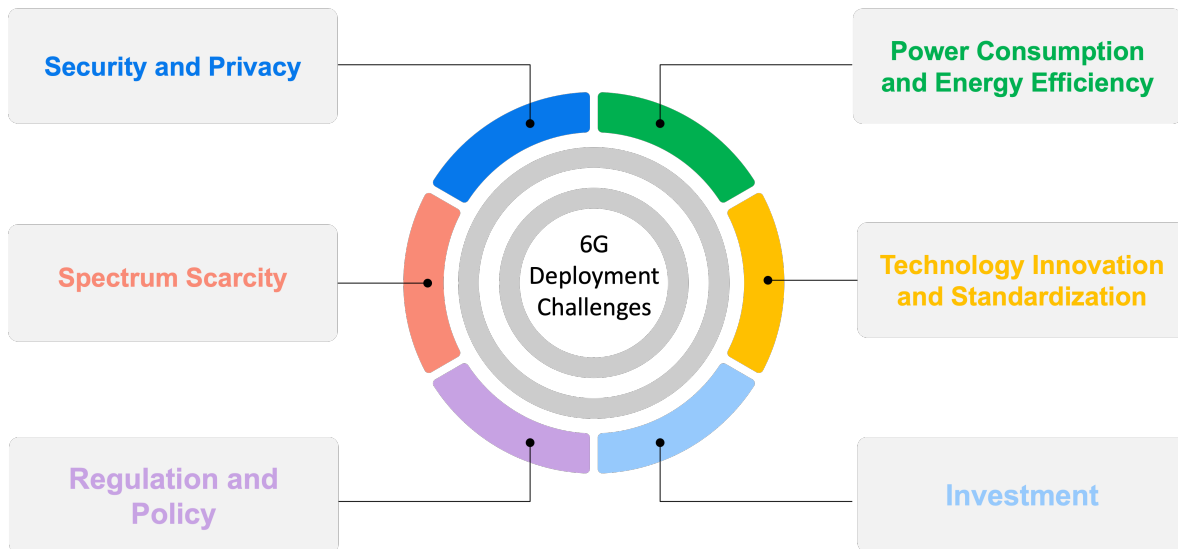
Figure 5. Challenges for 6G deployment .

- **Technology Innovation and Standardization** Technical difficulties in implementing new enabling technologies like millimeter- and terahertz-wave communication, massive and ultra-massive MIMO, artificial intelligence, machine learning, quantum communication, and ultra-reliable low-latency communication [75].

- **Bandwidth Scarcity** Identifying and allocating sufficient spectrum in the Terahertz (THz) frequency range for 6G is a significant challenge. THz frequencies offer the potential for high data rates but come with propagation challenges and require new regulatory frameworks [76].

- **Interoperability with Existing Networks:** Ensuring interoperability between different technologies across various industries and use cases is a complex challenge as many other networks use different standards and protocols [77].

- **Investment Cost** The deployment of 6G infrastructure is expected to be cost-intensive, requiring substantial investments in advanced technologies, equipment, and infrastructure. This might pose a financial challenge for network operators and end-users. This financial burden could hinder the broad adoption of 6G, especially in less economically developed regions and remote rural areas [78].

- **Regulation and Policy** Regulatory issues may arise due to new spectrum, and technologies used, necessitating developing and implementing new policies and regulations [79].

- **Power consumption** Power consumption is another concern, as the increased data rates and the number of devices connected to the network will result in higher power usage. Sharing spectrum and infrastructure, implementing cell-free massive MIMO, and integrating communication and sensing are all pivotal aspects. Yet, the paramount transformation with 6G lies in the shift to higher frequencies, surpassing the 100 GHz threshold [80].

- **International Collaboration and Harmonization** The competitive landscape, with multiple companies and countries vying to be the first to launch and deploy 6G. Promoting collaboration and harmonization of 6G standards and regulations on a global scale is crucial to ensure the success and widespread adoption of 6G technology will be challenging.

- **Security and Privacy** There will be new security concerns as the network will transmit large amounts of sensitive data. Besides increasing connectivity and integrating various devices and systems, security and privacy will be a significant challenge [81].

- **Environmental Concerns** The production of 6G infrastructure requires various raw materials, including rare earth metals and minerals. The extraction processes can have environmental and social impacts, contributing to habitat destruction, pollution, and resource depletion [82].

Table 2 Summarizes the 6G deployment challenges and possible solutions.

Table 2. Summary of challenges and possible solutions for 6G deployment.

Challenges	Possible Solution
Technology innovation and standardization	Establish testbeds to validate the performance of millimeter- and terahertz-wave communication in different environments. This includes testing for signal propagation, interference, and device compatibility. Invest in the research and development of signal processing algorithms that can efficiently handle the massive number of antennas involved in MIMO systems. This includes beamforming, channel estimation, and interference management [83,84].
Scarcity of high-frequency spectrum for bandwidth allocation	Collaborate with regulatory bodies to identify and allocate specific frequency bands for 6G, with a focus on millimeter and terahertz bands. This involves conducting spectrum studies to identify underutilized or unallocated frequency ranges[85].
Interoperability between current and 6G networks	The technologies should be built to interoperate with the existing network and devices [86].
Investment cost	Implement a phased approach to 6G deployment, focusing on specific geographic areas, use cases, or network functionalities. This approach minimizes heavy upfront costs [87].
Regulatory and Policy Challenges	Establish international agreements and collaborate with regulatory bodies to harmonize spectrum allocation for 6G. Encourage the development of dynamic spectrum sharing technologies to optimize spectrum utilization [88].
Power consumption	A model for optimizing power has been introduced for a 6G-enabled massive IoT network. The primary objective is to enhance overall system performance, providing energy-saving features. Through efficient power resource management, the model minimizes power overhead attributed to the extensive number of connected devices. The assessment of the proposed network includes an analysis of the maximum allocated power and spectral efficiency under various network operations and distinct precoding schemes [89].
International collaboration and harmonization	Encourage international collaboration in standardization bodies to develop unified standards for 6G technologies. Harmonize spectrum allocation, protocols, and interfaces to ensure interoperability and a consistent user experience [90].
Security and Privacy	While robust security mechanisms are in place for safeguarding data during transit, there is a pressing need to prioritize the protection of data in processing and storage for comprehensive end-to-end security in 6G. Techniques such as oblivious computing, confidential computing, homomorphic encryption, and privacy-centric identifiers can be employed across both 6G network services and components [91].
Environmental concerns	Design devices and infrastructure for longevity and ease of recycling. Establish collection and recycling programs for end-of-life electronic components. Encourage manufacturers to adopt sustainable product life cycles [92,93].

8. Key Technologies for 6G Deployment

Several key technologies are being explored and considered as potential components of 6G networks. We will discussing few major enabling technologies for 6G networks. (Figure 6).
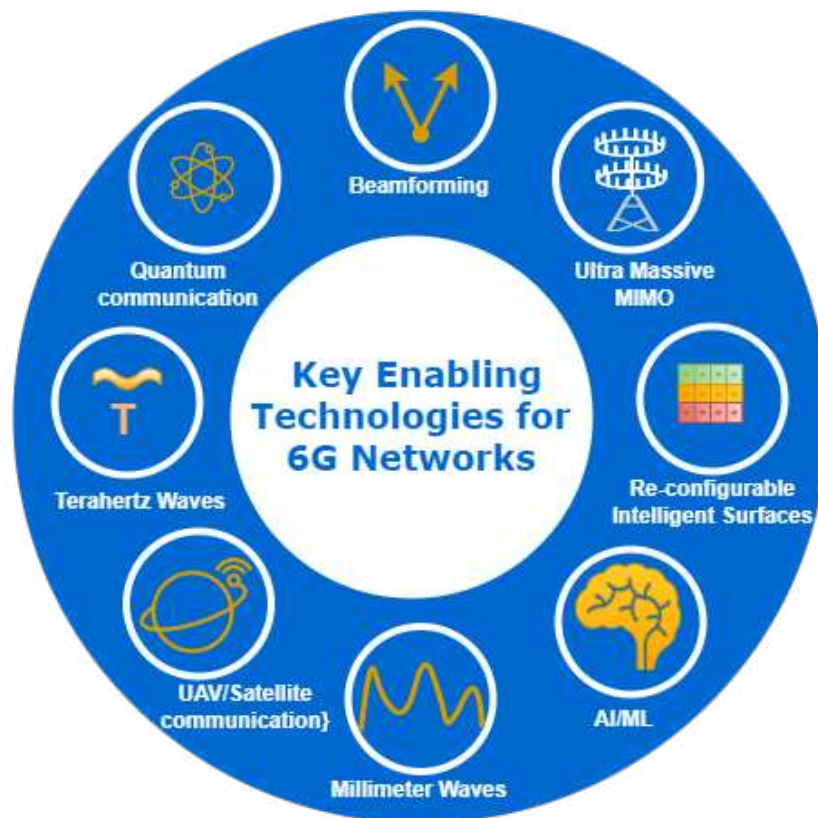
Figure 6. Overview of Key Enabling Technologies for 6G Networks - This diagram illustrates the advanced technological pillars essential for the deployment of 6G networks, including Quantum communication, Beamforming, Ultra Massive MIMO, Re-configurable Intelligent Surfaces, AI/ML, Millimeter Waves, UAV/Satellite communication, and Terahertz Waves. Each technology plays a crucial role in enhancing the data rate, reliability, and overall efficiency of future wireless communication systems.

8.1. Terahertz Communication

Terahertz communication is expected to significantly impact the development of 6G networks by offering faster and more efficient data transmission capabilities [112]. Terahertz communication provides higher data rates than current wireless communication technologies, resulting in faster download and upload speeds and improving the overall user experience. Moreover, terahertz frequencies provide more available bandwidth, allowing for more efficient spectrum use, reducing network congestion, and improving overall network performance [113]. Terahertz communication can enable new use cases, such as high-resolution imaging, remote sensing, and advanced medical imaging, which require higher data rates and lower latency [114]. By using short wavelengths that are difficult to intercept or detect, terahertz communication can enhance wireless communication security, reducing the risk of cyber-attacks and unauthorized access [115].

8.2. Ultra-Massive MIMO

Ultra-Massive MIMO technology, a key component in the evolution of 6G networks, offers significant advancements in network capacity, data rates, and coverage [116]. It utilizes a large array of antennas capable of transmitting and receiving multiple data streams simultaneously. This capability not only accelerates data transmission but also significantly boosts data rates [117]. Furthermore, Ultra-Massive MIMO enhances signal processing and improves beamforming, leading to higher energy efficiency and more effective spectrum utilization [118].

This technology also plays a crucial role in optimizing frequency spectrum use, thereby augmenting network capacity and enhancing coverage. Its ability to reduce interference substantially improves overall network performance [119]. Additionally, Ultra-Massive MIMO is instrumental in supporting emerging applications that demand higher data rates and lower latency. These applications include virtual reality, autonomous vehicles, and the development of smart city infrastructure [120]. Consequently, Ultra-Massive MIMO stands as a transformative technology, poised to revolutionize 6G network capabilities and facilitate a new wave of technological advancements.

8.3. Beamforming

Beamforming is a crucial technology that improves the efficiency and reliability of wireless communication and enables the development of 6G networks. This technology involves directing radio waves in a specific direction to achieve better spectrum use and network performance. In 6G networks, beamforming can focus wireless signals to the desired receiver, resulting in reduced interference and improved signal strength [?]. This leads to higher data rates, lower latency, and the ability to support real-time data transmission for new use cases like virtual reality, remote surgery, and autonomous vehicles. Beamforming technology enables more efficient use of the frequency spectrum by directing radio waves to specific areas [121]. This decreases interference and enhances network capacity, mitigating congestion and improving overall performance.

8.4. Cell-Free Massive MIMO

Cell-free Massive MIMO is a promising technology for the development of 6G networks, as highlighted in [122]. This technology involves deploying numerous antennas across a given area, enhancing the efficiency of wireless communication. Compared to traditional cellular networks, Cell-free Massive MIMO offers several advantages, including improved network coverage. This is particularly beneficial in dense urban environments, where it allows for more effective use of available radio resources, leading to better signal quality and fewer coverage gaps [123].

Additionally, Cell-free Massive MIMO can support a greater number of users per unit area, thus increasing network capacity. This feature is especially useful in areas with high user density, such as stadiums, airports, and other public spaces [124]. Another significant advantage of Cell-free Massive MIMO is the reduction in latency. By enabling multiple users to access the same channel simultaneously, it reduces waiting times and improves the overall user experience [125].

Furthermore, Cell-free Massive MIMO contributes to enhanced energy efficiency. By reducing the need for complex and power-intensive signal processing algorithms, it leads to lower power consumption and extended battery life for mobile devices [126]. These benefits make Cell-free Massive MIMO a transformative technology for future cellular networks.

8.5. Millimeter Waves:

Millimeter Waves (mmWave) operate within a frequency range of 30 GHz to 300 GHz and have shorter wavelengths than the traditional microwave bands used in 4G and 5G networks [127]. Its potential to deliver faster data speeds, higher network capacity, and improved network efficiency makes it a crucial enabler of 6G networks. MmWave technology provides several benefits, such as enabling high data rates of several gigabits per second and allowing for new use cases, such as augmented reality and 8K video streaming, that require high data rates and low latency. mmWave can increase network capacity, as the higher frequencies make more efficient use of the available spectrum.

However, the use of mmWave technology also poses challenges. One such challenge is the shorter range of mmWave signals compared to traditional microwave frequencies, making it easy for obstacles such as buildings and trees to block signals and affect network coverage [128]. Furthermore, deploying mmWave technology requires many antennas, resulting in high infrastructure costs that must be addressed to promote widespread technology adoption.

8.6. Re-Configurable Intelligent Surfaces

Re-configurable Intelligent Surfaces (RIS) are an emerging technology with significant potential to drive the development of 6G networks. Characterized by a flat surface embedded with numerous small antennas or reflectors, RIS can electronically control radio waves to reflect, amplify, or absorb them [129]. This capability offers several advantages for future network infrastructures.

One of the primary benefits of RIS technology is its ability to enhance network coverage. By placing RIS in areas with traditionally poor coverage or high signal interference, such as indoor spaces, it can effectively reflect and amplify signals. This improvement results in stronger signal strength and broader coverage. Additionally, RIS contributes to increased network capacity by enabling more efficient use of available radio resources. It accomplishes this by focusing radio waves in specific directions, thereby reducing interference and supporting a higher number of concurrent users.

Another significant advantage of RIS is its contribution to energy efficiency. By reflecting and focusing radio waves directionally, RIS minimizes the energy required for transmitting signals over long distances [130]. This leads to lower power consumption, prolonged battery life for mobile devices, and a reduction in the overall energy footprint of the network. The widespread implementation of RIS technology will necessitate substantial investments in infrastructure and technological advancements. Addressing these requirements is essential to fully leverage the capabilities of RIS in enhancing future network systems.

8.7. Quantum Communication

Quantum communication is an advanced technology that can be utilized in the development of 6G networks [131]. Unlike traditional communication technologies that rely on electromagnetic waves to transmit data, quantum communication uses photons for transmission. This feature allows quantum communication to offer high levels of security, making it ideal for military and government communications where the highest levels of security are required.

Quantum communication can also support new applications that necessitate real-time data transmission, such as autonomous vehicles and smart cities. By offering instantaneous communication over long distances, quantum communication can reduce latency and enable faster response times [132]. However, deploying this technology faces several challenges, such as the need for specialized hardware and infrastructure and high implementation costs.

8.8. UAV/Satellite Communication

UAV/Satellite communication is a technology that can facilitate the development of 6G networks [133]. This technology uses unmanned aerial vehicles(UAVs) and satellites to provide wireless connectivity to remote and underserved areas. By using these aerial platforms, it is possible to provide high-speed data transfer and internet connectivity to regions that are difficult to reach using traditional terrestrial networks. The potential for expanded network coverage, particularly in remote and rural areas with limited traditional infrastructure. This can enable more people to access high-speed internet and other data services, improving access to information and enabling new applications and services. UAV/satellite communication can also support new use cases that require real-time data transmission, such as remote medical procedures and disaster response [134]. By enabling communication over long distances and in rugged terrain, UAV/satellite communication can improve the efficiency and effectiveness of these applications. The deployment of UAV/satellite communication technology also presents challenges, such as the need for specialized hardware and infrastructure, as well as regulatory issues related to the use of airspace [135]. The technology requires significant satellite and UAV deployment and maintenance investment.

9. Is 6G Dangerous for Your Health?

Research on the potential health effects of 6G networks is limited, as the technology is still in its early stages of development. However, concerns have been raised about the possible risks of exposure to high-frequency electromagnetic radiation in 6G networks [136]. The World Health Organization has categorized electromagnetic radiation as a potential carcinogen, and specific research studies have associated exposure to high levels of electromagnetic radiation with an elevated likelihood of cancer and other health issues [137]. However, these studies have focused mainly on exposure to radiofrequency radiation from cell phones and other devices that operate in lower frequency ranges used by 4G and 5G networks [138]. While there is currently no evidence to suggest that exposure to the higher frequency electromagnetic radiation used in 6G networks poses a significant health risk to humans, more research is needed to understand this technology's potential health effects fully. According to the FCC, the frequency range designated for 6G is between 95 GHz to 3THz. Despite being three to a thousand times higher than 5G's frequency, these ranges are still considered safe as they are non-ionizing [139].
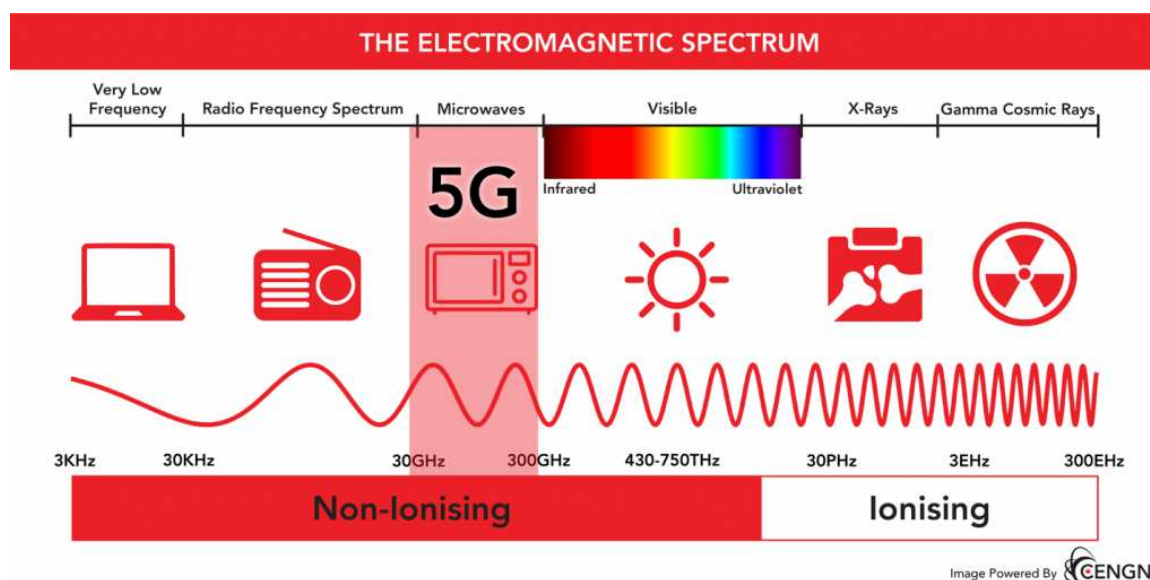

Figure 7. The electromagnetic spectrum. The frequency used by 6G is non-ionizing; thus, it is safe.

Exposure to electromagnetic radiation from 6G networks is likely to be significantly lower than that from other sources, as the technology will likely use a combination of different frequency ranges, including lower frequencies employed in earlier generations of mobile networks. Measures can also be taken to reduce exposure to electromagnetic radiation, for instance, restricting cell phone and wireless device usage, employing protective cases, and keeping devices away from the body when in use [140]. While there is currently no evidence to suggest that 6G networks are dangerous for human health, further research is needed to understand the potential risks of this technology.

10. Open Research Topics

1. *Investigation into Advanced Modulation and Coding Schemes:* Research is needed on new schemes adapted for the high frequency bands and extensive bandwidths of 6G. This includes studying techniques for enhanced spectrum utilization and improved data throughput, critical for reliable communication in various environments.

2. *Seamless Integration of Satellite and Terrestrial Networks:* There is a significant opportunity for research in the integration of satellite and terrestrial networks. This requires the development of new protocols and architectures to facilitate efficient network handover and connectivity, especially in remote areas.

3. *Application of Artificial Intelligence in Network Performance:* There is a wide scope for using AI to optimize 6G network operations. Research areas include predictive analytics, congestion management, and adaptive resource allocation based on real-time network conditions.

4. *Development of Energy-Efficient Solutions in 6G Networks:* As the number of connected devices grows, research into energy-efficient technologies for 6G networks becomes imperative. This involves creating low-power hardware solutions and sustainable network operation methods.

5. *Enhancing Security and Privacy in 6G Networks:* There is a pressing need for research into advanced security and privacy measures. This includes the development of new encryption techniques, secure communication protocols, and methods to ensure data privacy in an interconnected environment.

6. *Exploration of Quantum Communication in 6G:* Research into the application of quantum communication within 6G networks offers potential for secure and efficient data transmission. This includes studies on quantum key distribution, entanglement, and integration with existing telecommunications infrastructure.

7. *Identifying and Developing New Applications and Services:* There is a need for research into applications that exploit the capabilities of 6G, such as advanced virtual/augmented reality, autonomous vehicles, and smart city infrastructure, to unlock new possibilities and services.

8. *Research on Network Slicing and Customization:* Investigating network slicing as a method for providing tailored network services is a promising research area. This includes studies on resource allocation, network functionality customization, and quality of service optimization for different applications.

9. *Achieving Ultra-Reliable Low-Latency Communication:* Focusing on URLLC in 6G is crucial for supporting critical applications like remote healthcare and industrial automation. Research is needed to minimize latency, enhance reliability, and ensure consistent service quality.

11. 7G Networks

7G networks, currently a theoretical concept, are anticipated to significantly outpace the capabilities of 6G networks, introducing groundbreaking features such as holographic communication and brain-computer interfaces. Presently, the term "7G" has not been officially recognized by any standardization bodies, and the realization of these networks is projected to span several decades. This timeline is due to the substantial advancements needed in wireless communication technology and infrastructure.

The vision for 7G includes the potential use of beyond terahertz frequencies, which could dramatically increase data transmission speeds. Additionally, advancements in neuromorphic computing are expected to substantially enhance data processing efficiency. Among the other prospective features of 7G networks are highly sophisticated artificial intelligence, seamless inter-network connectivity, and novel applications like fully autonomous transportation systems.

Despite the exciting prospects that 7G networks present, their development poses significant challenges. These include the need for extensive investment in research and development, as well as considerable upgrades to existing communication infrastructure. Such developments are essential to make the leap from theoretical ideas to practical implementation, and this process is likely to span multiple decades.

12. Conclusions

This paper provides an in-depth exploration of the evolving landscape of 6G networks, highlighting the transformative role of Artificial Intelligence (AI) in this next wave of wireless technology. We presented hierarchical structure of 6G networks, scrutinizing the technological advancements driving its emergence, the potential applications, and the challenges it faces. We explored the evolutionary trajectory of wireless communication technologies, emphasizing how each

generation has progressively enhanced data rates, connectivity, and functionality. With the advent of 6G, we anticipate an unprecedented leap in these aspects, driven by key enabling technologies like terahertz communication, ultra-massive MIMO, AI, machine learning, quantum communication, and re-configurable intelligent surfaces.

The integration of AI into 6G networks emerged as a pivotal theme, promising to revolutionize network management and user experience. By leveraging AI's predictive and adaptive capabilities, 6G networks are poised to offer optimized bandwidth, enhanced efficiency, and more personalized services. The potential applications of 6G are vast and varied, ranging from enhanced mobile broadband to innovative domains such as smart cities, autonomous systems, and even brain-computer interfaces, underlining the network's transformative impact across sectors.

However, the journey towards actualizing 6G is not without its challenges. Technological hurdles, bandwidth scarcity, interoperability issues, investment costs, regulatory complexities, environmental concerns, and security and privacy issues represent significant barriers. Addressing these challenges requires a concerted effort from industry, academia, and regulatory bodies. As we venture into the speculative realm of 7G networks, we contemplate even more advanced features and capabilities. The prospect of holographic communication and neuromorphic computing in 7G underscores the continual evolution and boundless potential of wireless technology.

In conclusion, this paper serves not only as a comprehensive overview of 6G networks but also as a catalyst for further research and development in this field. It underlines the synergy between 6G and AI technologies and sets the stage for continued exploration and innovation. As the world gravitates towards increasingly connected and intelligent systems, the insights and discussions presented here will be instrumental in shaping the future of wireless communication.

Author Contributions: The authors declare that they have equally contributed to the paper. All authors read and approved the final manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
DOAJ	Directory of open access journals
TLA	Three letter acronym
LD	Linear dichroism
AMPS	Advanced Mobile Phone System
TACS	Total Access Communication System
NMT	Nordic Mobile Telephone
SMS	Short Message Service
PDC	Personal Digital Cellular
WCDMA	Wideband Code Division Multiple Access
MMS	Multimedia Message Support
RL	Reinforcement Learning
RIS	Re-configurable Intelligent Surfaces

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