The Convergence of AI, 6G, and Wireless Communication

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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. By integrating AI and ML, 6G networks are expected to offer unprecedented capabilities, from enhanced mobile broadband to groundbreaking applications in areas like smart cities and autonomous systems.

Keywords: 6G ; artificial intelligence (AI) ; cloud gaming ; smart grid ; brain–computer interfaces (BCIs) ; blockchain ; deep-sea sightseeing ; tactile internet

1. Introduction

As globalization advances, 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 and is projected to reach 2194 exabytes per month by 2028 and 5016 exabytes per month by 2030 [1].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 [2]. The growing demand for mobile data services is not limited to a particular region or demographic [3]. 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, AI, blockchain, augmented and extended reality, 3D video, and connected vehicles [4].

5G technology has been deployed worldwide [5] to meet the increasing need for mobile data services. 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. 6G networks will transform mobile networks by integrating AI and ML to seamlessly combine the physical, digital, and biological worlds. 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 [9].

With 6G technology, a wide array of possibilities unfolds across three key services: enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC) [10]. The above use cases are described in detail below:

(a)**Enhanced mobile broadband (eMBB):** 6G networks are expected to further improve upon the enhanced mobile broadband capabilities of 5G by delivering even higher data rates, lower latency, and increased capacity [11]. Some potential aspects of eMBB in 6G networks include the following:

- Ultra-high data rates: 6G networks could achieve significantly higher data rates compared to 5G, potentially reaching terabits per second (Tbps) speeds [12]. This would enable seamless streaming of immersive, high-resolution content such as holographic videos, uncompressed 8K or 16K video streaming, and ultra-HD virtual reality (VR) and augmented reality (AR) experiences.

- Low-latency communication: 6G networks aim to further reduce latency to near-real-time levels, enabling ultra-responsive applications such as cloud gaming, remote surgery, and autonomous vehicles. With latency reduced to microseconds or even nanoseconds, users can experience seamless interactions with remote systems and devices [13].

- Massive capacity: 6G networks are expected to support a massive increase in connected devices and simultaneous connections, facilitating the proliferation of IoT devices, wearable technologies, and smart sensors [14]. This would enable seamless connectivity and data exchange in densely populated areas or scenarios with a high density of connected devices.

(b)**Ultra-reliable low-latency communication (URLLC):** 6G networks will build upon the ultra-reliable low-latency communication capabilities of 5G by further reducing latency and increasing reliability. Key aspects of URLLC in 6G networks include the following:

- Mission-critical applications: 6G networks will support mission-critical applications that require ultra-low latency and high reliability, such as industrial automation, remote surgery, and autonomous vehicles. By reducing latency to sub-millisecond levels and ensuring ultra-reliable communication links, 6G networks will enable seamless connectivity and real-time responsiveness in critical scenarios [15].

- Predictive maintenance: With advanced analytics and AI integration, 6G networks can enable predictive maintenance in industrial settings, allowing machines and equipment to communicate in real time and anticipate maintenance needs before failures occur. This proactive approach to maintenance can minimize downtime, reduce operational costs, and optimize asset performance [16].

(c)**Massive machine-type communication (mMTC):** 6G networks will continue to support massive machine-type communication, catering to the connectivity needs of many IoT devices and sensors. Key aspects of mMTC in 6G networks include the following:

- Massive scalability: 6G networks will be designed to support a massive scale of connected devices, ranging from billions to trillions of IoT devices and sensors [17]. This scalability will enable the deployment of IoT solutions in various domains, including smart cities, industrial automation, agriculture, healthcare, and environmental monitoring.

- Energy-efficient communication: 6G networks will incorporate energy-efficient communication protocols and techniques to optimize power consumption in IoT devices and extend battery life [18]. This will enable long-lasting and sustainable IoT deployments, particularly in remote or inaccessible locations where power sources are limited.

- Diverse use cases: 6G networks will support diverse IoT applications with varying requirements in terms of data rates, latency, reliability, and energy consumption [19]. These applications include smart grids, asset tracking, environmental monitoring, smart agriculture, and smart healthcare, among others.

Table 1 compares 5G and AI-revolutionized 6G technology across enhanced mobile broadband, ultra-reliable low-latency communication, and massive machine-type communication.

Table 1. A comparison between 5G and AI revolutionized 6G technology across eMBB, URLLC, and mMTC.

Technology	Enhanced Mobile Broadband (eMBB)	Ultra-Reliable Low-Latency Communication (URLLC)	Massive Machine-Type Communication (mMTC)
5G	**Provides high data rates for mobile users, enabling high-definition video streaming [20].**	**Offers reliable and low-latency communication, crucial for applications such as industrial automation and remote surgery [21].**	**Supports a large number of connected devices, enabling efficient communication between a massive number of IoT devices [22].**
AI-revolutionized 6G	**Leverages AI for better spectrum utilization and intelligent resource allocation [23].**	**Improves URLLC with even lower latency and higher reliability through AI-powered network optimization and predictive maintenance capabilities [24].**	**Optimizes resource allocation and communication protocols for efficient device-to-device communication and network slicing [25].**

2. Applications of 6G Network

The 6G network is not yet commercially available; however, it is expected to have applications in several domains [26].

Figure 1 below shows the applications of 6G networks.

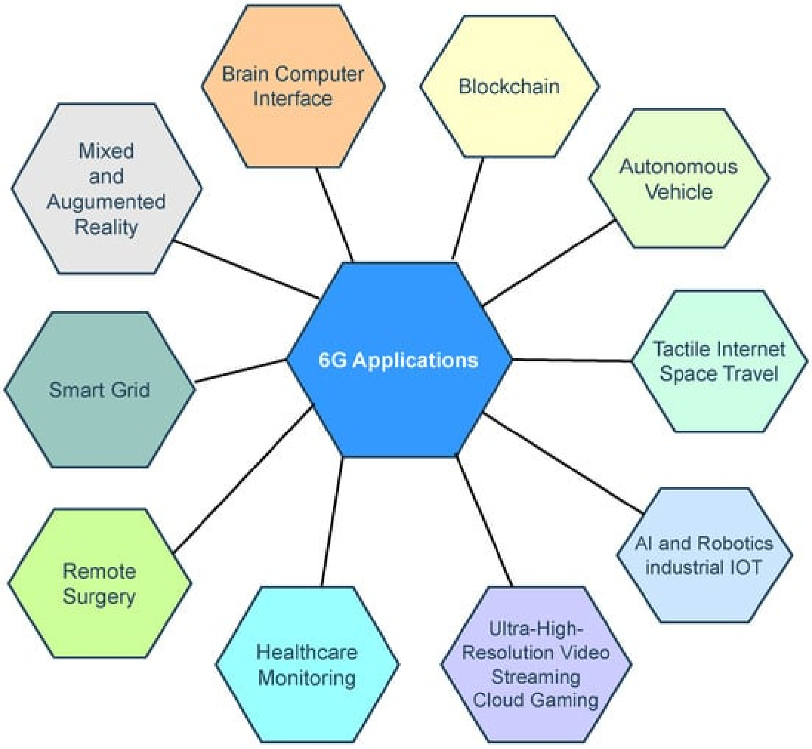

Figure 1. Applications of 6G networks.

2.1. Ultra-High-Resolution Video Streaming and Cloud Gaming

The advancement of the 6G network and the AI revolution will enable seamless streaming of ultra-high-resolution video content and cloud gaming experiences with unprecedented quality and minimal interruptions [27]. Complementing this infrastructure, the AI revolution will leverage sophisticated algorithms to optimize streaming parameters in real time, ensuring smooth playback and personalized content recommendations based on user preferences. Together, this integration of 6G networks and AI technologies will revolutionize the entertainment landscape, offering users immersive, high-quality experiences that redefine the boundaries of mobile communication and AI.

2.2. Healthcare Monitoring

The convergence of AI and the 6G revolution is poised to revolutionize health monitoring applications by enabling real-time data processing, remote monitoring, personalized healthcare, predictive analytics, healthcare automation, and enhanced diagnosis and treatment [28]. The ultra-low latency and high data transfer speeds offered by 6G networks will facilitate the seamless transmission and analysis of health data, allowing for timely interventions and personalized healthcare recommendations based on individualized data insights. AI algorithms will be crucial in analyzing vast datasets to identify patterns and correlations, enabling predictive analytics for forecasting health trends and automating various healthcare processes [29]. This synergy between AI and 6G technologies promises to optimize patient care by providing more efficient, proactive, and personalized healthcare delivery.

2.3. Remote Surgery

The emergence of telesurgery, enabled by robotic technology and wireless networking, revolutionizes surgical practice by connecting geographically distant patients and surgeons [30]. This innovative approach harnesses the power of advanced telecommunications and robotics, facilitated by the anticipated 6G network revolution and artificial intelligence technologies. The 6G network's ultra-fast data transmission speeds and ultra-low latency ensure seamless communication between remote robotic surgical systems and surgeons, overcoming geographical barriers and providing high-quality surgical care in remote locations [31]. AI-powered robotic systems exhibit precise and dexterous movements, augmented by AI algorithms that continuously learn and adapt to improve surgical outcomes. Real-time data processing and analysis by AI algorithms enable remote surgeons to make informed decisions during telesurgery procedures, enhancing patient safety and surgical precision. Overall, integrating 6G networking capabilities and AI technologies in telesurgery advances surgical practice by improving access to care, enhancing surgical outcomes, and ensuring patient safety.

2.4. Smart Grid

Due to the integration of 6G and artificial intelligence, a significant revolution is underway in the development and functionality of smart grids. 6G networks are anticipated to offer ultra-fast data transmission speeds, ultra-low latency, and extensive device connectivity, thereby significantly improving the communication infrastructure of smart grids [32]. This will enable the real-time monitoring, control, and optimization of energy distribution and consumption within the grid, facilitating efficient energy management and response to dynamic demand patterns. AI technologies, when integrated with 6G networks, further enhance the capabilities of smart grids by enabling advanced analytics, predictive modeling, and autonomous decision making. AI algorithms can analyze vast amounts of data collected from sensors, meters, and other grid components to identify patterns, predict potential issues, and optimize grid operations in real time [33]. This synergy between 6G and AI revolutionizes the efficiency, reliability, and resilience of smart grids, paving the way for a more sustainable and intelligent energy infrastructure.

2.5. 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 [34]. 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 [35]. 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 can potentially 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.

2.6. Blockchain

Blockchain is a system that allows for the secure and transparent recording of digital transactions in a decentralized manner [36]. 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 [37]. 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. 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.

2.7. 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 [38]. The fast data transfer speeds offered by 6G allow 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.

2.8. Deep-Sea Sightseeing

Applying 6G in deep-sea sightseeing could 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 [39]. This could allow for the transmission of 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 [40]. 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.

2.9. 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 [41]. 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. Additionally, 6G's advanced communication technologies, such as edge computing and terahertz communication, may enable the development of compact and highly accurate haptic devices [42]. 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.

2.10. Industrial Internet of Things

The combination of 6G and the potential for transformation lies within the Industrial Internet of Things (IIoT) industrial operations [43]. 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 the predictive maintenance and remote control of industrial systems [44]. With its ability to drive the creation of intelligent and automated industrial systems, 6G has the potential to increase productivity and efficiency and to lower costs.

2.11. 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 [45]. 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 to occur. 6G's enhanced network security measures can provide peace of mind, protecting sensitive information and user data from cyber threats [46]. 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.

2.12. AI 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 [47]. 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 the 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. The increased connectivity and capabilities of 6G networks will also drive the creation of new and innovative AI-powered applications and services.

2.13. 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 [48]. 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 [49]. 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 [50].

2.14. Mission-Critical Services (MCSs)

6G networks offer a transformative platform for enhancing mission-critical services (MCSs) through ultra-reliable low-latency communication, real-time monitoring and control of critical infrastructure, integration with edge computing and AI for predictive analytics and decision making, advanced public safety and emergency response applications, development of smart infrastructure and utilities for improved efficiency and resilience, support for telemedicine and remote healthcare services, and robust cybersecurity measures to protect sensitive data and infrastructure from cyber threats. These capabilities enable timely decision making, seamless coordination among emergency services, enhanced reliability of essential services, and improved accessibility to critical care, ultimately ensuring MCSs' reliability, responsiveness, and efficiency across various sectors [51].

2.15. Public Protection and Disaster Relief (PPDR)

The advent of 6G networks presents many transformative applications for public protection and disaster relief (PPDR) efforts. Through ultra-high-speed, low-latency communication, 6G facilitates the real-time data transmission essential for swift decision making and coordination among emergency responders during crises [52]. Integration with augmented reality (AR) and virtual reality (VR) technologies enhances situational awareness and navigation in disaster zones. At the same time, AI-powered predictive analytics enables proactive PPDR strategies by analyzing vast datasets to anticipate risks and optimize resource allocation. Seamless integration with drones and UAVs enables aerial surveillance and search-and-rescue missions, while biometric identification and wearable technologies ensure the safety and accountability of personnel in disaster areas. Advanced security measures safeguard sensitive PPDR data and communication infrastructure, while community engagement platforms empower citizens to participate actively in disaster preparedness and response efforts. Overall, 6G networks hold immense potential to enhance the effectiveness, efficiency, and resilience of PPDR initiatives, ultimately saving lives and mitigating the impact of disasters on communities [53].

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