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Review On Revolutionizing Connectivity :The Transformative Impact of 6G Technology on Telecommunications

[1]Ashwin K S
student
Alva's Institute of Engineering and technology
[1]ashwinkugati0712@gmail.com

[2]B Prakash
student
Alva's Institute of Engineering and technology
[2] bprakashjk2000@gmail.com

[3]Balaji Sathish Kulkarni
student
Alva's Institute of Engineering and technology
[3]balajiskulkarni@gmail.com

[4]Bharat
student
Alva's Institute of Engineering and technology
[4]bharathmk185@gmail.com

[5]Mr. Ramachandra H Y
Assistant Professor
Alva's Institute of Engineering and technology
[5]ramachandrahy@aiet.org.in

Abstract

6G technology, positioned to surpass 5G, holds the potential to revolutionize telecommunications and connectivity by offering ultra-high data rates, improved bandwidth, and minimal latency. These advancements will pave the way for a wide range of new services and applications across various sectors, including smart cities, autonomous systems, augmented and virtual reality, and remote healthcare. To gain insights into the future applications of 6G, comprehensive analyses of different service scenarios are being conducted in both academia and industry. By utilizing public data, research papers, corporate reports, and news articles, researchers have identified four major domains and sixteen application areas. Evaluations using future-context and business model canvases have revealed the potential value of these services from the perspectives of both users and suppliers.6G technology will address the limitations of 5G, particularly in data-intensive, low-latency, and high-reliability applications. The integration of artificial intelligence will enhance capabilities in areas such as object localization, UAV communication, and security. The development of digital twin worlds, new man-machine interfaces, ubiquitous computing, and multi-sensory data fusion will redefine connectivity and interaction. Key technological transformations will include cognitive spectrum sharing, new spectrum bands, integrated localization and sensing, and innovative network architectures. As research progresses towards full adaptation by 2030, significant challenges such as infrastructure investment, cybersecurity, and ethical considerations regarding data privacy and the digital divide must be tackled. The deployment of 6G networks will shape the future of global connectivity, driving technological innovation and supporting emerging applications that surpass the capabilities of current communication standards.

I. INTRODUCTION

As 5G mobile communication networks are being deployed worldwide, researchers are already looking ahead to the next generation, known as 6G, to address the increasing demands of a data-driven society. Throughout the last forty years, a new generation of mobile networks has emerged roughly every decade, each improving human connectivity and capabilities. The progression began with zeroth-generation (0G) radio communication devices such as walkie-talkies, followed by first-generation (1G) analog voice communication in the 1980s. The second generation (2G) saw the transition to digital communication, supporting SMS. The third generation (3G) introduced mobile broadband, enabling video calls and mobile TV, while the fourth generation (4G) brought all-IP communication, VoIP, and high-definition video streaming [1]. 5G has taken mobile broadband (eMBB), ultra-reliable low latency communication (uRLLC), and massive machine-type communication (mMTC) to new heights, offering peak data rates of up to 10 Gbps, latency as low as 1 ms, and significantly increased device connectivity. This has facilitated the development of applications like VR, AR, autonomous vehicles, IoT, and Industry 4.0, supported by technologies such as network softwarization. Emerging communication paradigms like Edge Intelligence (EI), THz communication, Non-Orthogonal Multiple Access (NOMA), Large Intelligent Surfaces (LIS), swarm networks, and Self-Sustaining Networks (SSN) are evolving to drive future networks. Envisioned mainstream applications include Holographic Telepresence (HT), UAVs, Extended Reality (XR), smart grid 2.0, Industry 5.0, and space and deep-sea tourism, which require ultra-high data rates, real-time computing, low latency, precise localization, and high reliability—needs that surpass the capabilities of 5G. The progression towards the Internet of Everything (IoE) highlights the necessity for 6G, which seeks to seamlessly connect vast arrays of sensors, devices, and Cyber-Physical Systems (CPS). The connectivity of the future aims to enable the seamless integration of physical, biological, and digital worlds, creating unified experiences for humans and paving the way for advanced applications and unprecedented capabilities in the 6G era [2].

Recently, the emergence of 6G technology has become a key driver of national competitiveness, with a strong focus on leading in technology development and acquiring standards. 6G offers ultrahigh speed, ultra low latency, ultrawide bandwidth, and high energy efficiency compared to 5G. These advancements are propelling progress in various sectors such as autonomous driving, smart cities, and the medical industry. The Industry X.0 revolution in manufacturing is anticipated to be achieved through extensive IoT and AI integration, enabling full automation and remote issue resolution using digital twins and robots. The tactile Internet in holographic communication will allow real-time control and response, transitioning from content delivery to remote technology [3].

Numerous research studies have delved into the potential of 6G, with a focus on its impact on the United Nations Sustainable Development Goals (SDGs), multimodal data collection, and improved vehicle-to-everything communication. These studies emphasize the swift transition from 5G to 6G, the importance of coopetition and standardization, and the necessity of thoroughly examining the possibilities of 6G.To gain a comprehensive understanding of the societal impact of 6G, it is crucial to synthesize scenarios across various sectors. This particular study conducted an analysis of public data, including research papers, corporate reports, and news articles, in order to identify key domains such as immersive reality, intelligent manufacturing, smart infrastructure, and extended network. A methodology was developed to derive 6G service scenarios, which were then validated by experts, resulting in the identification of ten promising services. This study offers integrated and systematic insights into future 6G services by leveraging academic research, corporate reports, and news trends. It also provides a valuable tool for constructing future scenarios, enabling the analysis of the 6G ecosystem and guiding researchers and enterprises. Through this comprehensive analysis, the understanding and feasibility of 6G services are enhanced, ultimately promoting technology development through stakeholder consensus. In conclusion, this study significantly contributes to the understanding and maximization of the potential of 6G technology [4].

II. AI AND MACHINE LEARNING IN THE EVOLUTION OF WIRELESS NETWORKS: FROM 5G TO 6G:

Over the past ten years, AI and ML techniques particularly deep learning have grown quickly and are now essential to a wide range of image categorization and computer vision applications, from social networks to security. Large volumes of data are now available for training, which has fueled these breakthroughs. Reinforcement learning, for example, is being used more and more in robotic control applications as a result of its success in game contexts such as AlphaGo. Deep learning techniques have been extensively explored recently for use in wireless networks [5].

In the upcoming years, at least three significant applications of AI and ML to 5G systems are projected. First off, a number of model-based Layer 1 and Layer 2 algorithms, including channel estimation, preamble recognition, equalization, and user scheduling, may be able to be replaced by AI/ML for increased performance or reduced complexity[3]. Second, deployment optimization will make extensive use of AI and ML, including selecting the optimal subsets of beams to illuminate coverage areas based on cell traffic patterns. 5G systems are complex, requiring a great deal of setup before deployment; hence, AI/ML techniques are essential to enabling zero-touch network optimization. Third, use cases such as the more precise localization of end devices using 5G technology will be enhanced by the use of AI and ML. Extensive assessments, which include a synopsis of quantum computing and communications, fully detail the possible applications of AI and ML to 5G systems and beyond[8].

AI/ML will be essential for 5G end-to-end network automation, managing the complexity of orchestration across numerous network domains and levels, in addition to its application in the Radio Access Network (RAN). This would greatly lower operating costs by enabling immediate failure mitigation, quick deployment of new services, and dynamic adaptation of network and cloud resources in response to shifting needs. The idea of a completely automated, self-optimizing network architecture that reduces the need for human intervention will be made easier by AI and ML[8],[9].

We believe that 6G systems will use AI/ML at a deeper level than 5G systems did, moving from AI as an add-on to AI as the basis for air interface design and optimization. Context awareness, cognitive spectrum use, and self-optimizing transmitters and receivers are all included in this. The use of AI in wireless network design and optimization has gained a lot of traction due to advancements in the field, especially in deep learning and the availability of large amounts of training data. While AI is projected to be a key component of 6G, it is likely to play a major role in 5G, working mostly in remote places with large amounts of training data and strong processing facilities [6].

Physical layer designs like channel estimation and precoding, network resource allocation like traffic control and cache storage management, security and authentication, dynamic cell and topology formation and management, fault prediction and detection, and security are examples of successful AI applications in wireless communications. However, deep learning, which depends on centralized training, has problems with 6G's distributed architecture because of things like fog-RAN, which manages millions of end-to-end connections worldwide. Federated learning partially resolves this problem by enabling training at dispersed sites, but it still implements centralized learning in a distributed manner. An integrated strategy spanning the whole network, from the device level up, is needed to achieve full AI in 6G.

The intelligent 6G autonomous networks will require the combination of AI and game theory so that numerous AI agents may interact with one another and learn from one another. The idea of "collective AI," which blends artificial intelligence and game theory, would enable 6G by providing dispersed learning methods that let AI agents accomplish shared objectives through local training while limiting or eliminating direct agent-to-agent contact. By fully using radio waves for real-time communications and converting cognitive radio into intelligent radio, this integration will give 6G the mental capacity it deserves[7].

In conclusion, AI/ML will not only improve but also radically change the design and functionality of wireless networks as 5G and 6G advance. AI technologies will address present issues and open new possibilities as they develop and become more integrated. This will have a revolutionary effect on wireless communication networks. With artificial intelligence (AI) at its foundation, 6G promises to be a more intelligent, effective, and adaptable network infrastructure in the future, providing seamless and safe connections for a world going more and more digital.

III. KEY ENABLING TECHNOLOGIES

Enhancing Security and Privacy

Previous network improvements prioritized user capacity, speed, and dependability. Higher frequencies and network densification solved them, but security and privacy issues haven't gotten the same attention. New solutions are required since traditional encryption technologies are becoming susceptible. In order to improve data protection, 6G investigates quantum key distribution and PHY security. Furthermore, sophisticated communication technology might lead to strong cybersecurity. Because so much data is gathered, data providers run the danger of user information leaks. In 6G networks, blockchain technology is thought to provide anonymity, decentralization, and untrace ability.

In order to attain wireline-grade dependability, 6G needs strong security and privacy protocols. Industrial networks are particularly susceptible to operational disruption caused by jamming attacks. 6G needs to be capable of fending off these attacks. In order to preserve privacy inside dynamic sub-networks, authorization mechanisms will also move from the network level to the sub-network level, with a distinct division between them. With the convergence of the real and digital worlds, current privacy measures may not be sufficient. In order to enforce privacy choices, users will want control over the shared content they share, necessitating sophisticated data processing. One important aspect of 6G is security in mixed-reality contexts, which is addressed by emerging signal processing algorithms. Physical layer security techniques may also advance to meet new difficulties in the 6G future. These techniques depend on distinct wireless channels for key exchange, secrecy, and authentication.. Ultimately, user trust in the network's security will be critical for 6G's success.

UAV Wireless Networks and Mesh Connectivity

UAV wireless networks, which advocate using flying base stations to offer mobile coverage in areas where there is no infrastructure or where infrastructure is severely destroyed due to catastrophic events and reconnaissance activities, are one hot issue at the late stage of the of the development of 5G. Drone cells, or

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unmanned aerial vehicle (UAV) wireless networks, will reach their full potential in 6G and find widespread application in mobilizing network resources to provide cell-free networks with arbitrarily tiny latency. The optimization of resource allocation, including radio, energy, and computer resources, trajectory, content caching, and user association, will be accomplished concurrently in order to fully use the fluid cells generated by UAVs. UAVs will act as content providers and computing servers in 6G, in addition to being flying base stations for radio coverage. There will be a great deal of overlap with other new technologies. AI, for instance, will examine network usage data to determine the optimal routes for unmanned aerial vehicles (UAVs) and optimize other parameters, ultimately resulting in dynamic network topology reconfigurations. Wireless Power Transfer (WPT) technologies will also be very helpful to UAVs since they can allow service-based network slicing and keep them running constantly[5].

In order to attain greater network performance, 6G systems are predicted to undergo radical network modifications, moving away from traditional operating approaches. Redefining the idea of network cells in order to develop distributed MIMO, or cell-free networks, is one possible path. A centralized processing unit is connected to a number of access points (APs) that are uniformly located across the coverage area and have antennas installed in order to provide coordinated user service. Maintaining a consistent level of service quality for all customers is one of the many advantages of this network topology, particularly when huge MIMO systems are in place. Since non-standalone 5G architecture has been implemented, dual connectivity—in which a device is linked to both LTE and NR cells—has been firmly established in access. It is also expected that NR-NR dual connections will be implemented due to the requirement for high dependability. A device that has dual connectivity is linked to both a slave cell and a master cell. The goal of standardizing integrated access and backhaul (IAB) is to increase the range of high-band wireless links. Layer 2 IAB nodes store and send donor node packets without preserving any higher-layer user plane or UE control plane information. True mesh connection, in which a device may connect to the network via several paths, will be achieved by enabling dual connectivity for IAB nodes and end devices[14].

It is possible to create mesh connections with even greater densities by expanding dual to multi-connectivity at each hop. Furthermore, devices can become cell-free with state kept exclusively at the CP and UP anchors in the edge cloud thanks to the cloud implementation of the 6G Control Plane (CP) and User Plane (UP) capabilities. A mesh network can be created by routing packets through basically stateless lower-layer operations. The idea of many signals for various devices being broadcast concurrently from several radio units is also made possible by this cell-free mesh connection design, resulting in a distributed MIMO array and extremely high spectral efficiency. In order to maintain wide-area connections, 6G devices can also be locally linked to many proximal peer devices to build 6G sub-networks. In order to enable the high dependability and low latency required for Industry 4.0 applications, a sub-network connection will be essential. In other cases, devices might have several connections to terrestrial and satellite networks at the same time, offering different data pathways. In order to enable mobility within the network, the 6G architecture needs to be built to natively allow mesh connections. This is accomplished by putting the device's user plane and control plane anchors in the cloud and separating them from radio cells[13].

Terahertz Communication

To achieve the extremely high data rates required for 6G, a higher spectrum will be essential. The Terahertz (THz) band, covering frequencies between 0.1 THz and 10 THz with corresponding wavelengths from 0.03 mm to 3 mm, will be pivotal in facilitating these high data rates. The THz band offers extensive bandwidth, necessary for supporting these high data rates, but it also results in significant path loss[29]. Consequently, highly directional antennas will likely be crucial. These antennas, which have narrow beamwidths, reduce interference. Additionally, the small wavelength in the THz band allows for the integration of a larger number of antenna elements. This supports the use of advanced adaptive array technologies, which can mitigate the range limitations associated with THz communications[27].

Reconfigurable Intelligent Surface (RIS)

Reconfigurable Intelligent Surfaces (RIS) are a cutting-edge technology that aims to manageably modify the wireless environment by dynamically controlling electromagnetic waves between transmitters and receivers. RIS are often made out of a flat surface with many passive scattering components that may individually apply different phase shifts and occasionally amplitude increases to the incoming waves on their own. It is possible to precisely control the behavior of reradiated electromagnetic waves by adjusting these phase shifts and amplitudes. RIS employs primarily passive components rather than costly active components like power amplifiers, which drastically lowers installation costs and energy usage compared to 5G's relays and repeaters[12]. As a result, RIS is regarded as an ecologically benign and sustainable technology. However, the absence of digital signal processing capabilities and power amplifiers poses some design issues, including those related to amplification, signal regeneration, and channel estimation. New kinds of RIS, such as active RIS with certain active components for channel estimation and power amplification, are being researched as a solution to these problems. In addition, research is being done on AI, compressed sensing, and sophisticated signal processing methods to enhance RIS performance[10].

Quantum Communications

Unsupervised reinforcement learning may be implemented using 6G networks. 6G systems will not create large volumes of data that need labeling, which is necessary for supervised learning but not for unsupervised learning. Consequently, sophisticated network representations may be produced autonomously via unsupervised learning. The integration of unsupervised and reinforcement learning can lead to a completely autonomous network functioning. At first, it was thought that quantum computing and quantum machine learning would be essential to the development of 6G networks[1],[23].

Advanced Access-Backhaul Integration

The backhaul capacity will need to be increased in proportion to the huge data rates that future 6G access technologies are expected to deliver. There will be more access points as a result of the deployment of terahertz and visible light communication (VLC) technologies, and each access point will need backhaul connectivity to nearby access points and the core network. 6G technologies can take advantage of this by using their enormous capacity for self-backhauling solutions, in which base station radios manage both access and backhaul tasks. While this strategy is being investigated for 5G, the large-scale implementation of 6G will present new opportunities as well as obstacles. For example, in order to effectively handle the growing complexity, networks will need to have improved autonomous configuration capabilities.

IV. USE CASES AND TECHNICAL REQUIREMENTS

Massive Machine Type Communications (mMTC), Ultra-Reliable and Low Latency Communications (URLLC), and Enhanced Mobile Broadband (eMBB) are just a few of the features that 6G will expand upon and improve upon in comparison to 5G. It will also launch innovative services including holographic communications, immersive extended reality (XR), tactile and haptic internet applications, and communication as social infrastructure.\

XR: Extended Reality

Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are all included in XR, which provides immersive experiences through real-time user interactions and multi-sensory inputs[27]. In contrast to 5G, 6G promises very high data speeds, minimal latency, and incredibly dependable wireless connectivity, all of which will enable the smooth streaming necessary for XR. Applications for XR might be found in a number of industries, including manufacturing, entertainment, healthcare, and education. These industries all need high processing power and data rate performance[28].

Social Infrastructure: Communication

In order to solve problems like poverty, inequality in education, and climate change, wireless communication is becoming a more important part of social infrastructure. By 2030, the Sustainable Development Goals (SDGs) of the UN seek to resolve these problems and accomplish sustainable development. By facilitating access to information, resources, and social services through sophisticated information and communication technologies (ICT) without time or place limits, 6G will be crucial in achieving these goals[27]. .

Holographic Communications

Multimedia has advanced significantly with holographic displays, which can send 3D pictures to many locations and provide an immersive experience. Because of the intricacy of holograms, this technology needs extremely high data rates and very low latency in order to provide interactive features. Massive bandwidths, minimal latency to avoid simulator sickness, exact synchronization for multi-sensory integration, strong security, and system resilience are among the essential needs. 6G seeks to address current drawbacks, such as the requirement for head-mounted displays (HMDs) and high processing costs[21],[22].

Human Bond Communications

6G is anticipated to significantly advance human-centric communication, enabling individuals to access and share physical features seamlessly. The concept of human bond communication aims to incorporate all five human senses into the communication framework. This idea has recently expanded with the 'communication through breath' scheme, which involves reading a person's bio-profile through exhaled breath and interacting with the body via inhalation using volatile organic compounds. This innovation opens up possibilities for remote disease diagnosis, emotion detection, biological feature collection, and interaction with the human body[25],[26].

Developing such advanced communication systems that replicate human senses and biological features necessitates interdisciplinary research. It is expected that hybrid communication technologies will emerge, capable of sensing various physical quantities and securely sharing this information with intended recipients. This evolution will require a convergence of expertise from multiple fields to realize the full potential of 6G's human-centric communication capabilities[24].

Tactile and Haptic Internet Applications

Several applications fall under this category, including :

1)Robotic and Industrial Automation: In the context of cyber-physical systems (CPS), Industry 4.0 anticipates networks enabling human-machine collaboration. This covers sophisticated robotics and remote industrial management that need low latency and real-time control[15].

2)Driverless Operations: Autonomous driving, made possible by vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) connections, attempts to lower the number of collisions and traffic jams. Real-time coordination and collision avoidance depend on minimal latency[16].

3)Healthcare: By utilizing haptic and audio-visual feedback in real-time, telediagnosis, remote surgery, and tele-rehabilitation are possible uses. For such applications, which demand high data rates and sub-millisecond latency, the tactile internet will be indispensable[17].

Technical Requirements for Tactile Internet and Holographic Communications

Important specifications for the network include:

1)Data Rates: 4K 360° video requires 15–25 MB/s, whereas high-definition video requires 1–5 MB/s. Large holograms require between 0.5-2 Gb/s and many Tb/s[18].

2)Latency: various human senses need various reaction times; tactile signals, for example, require latency as little as 1 ms. For applications like robots and haptic feedback to avoid cybersickness, sub-millisecond latency is essential. Synchronization: To guarantee coherent processes, especially in machine control, real-time inputs from many locations must be synced[19].

3)Security: To avoid potentially fatal errors, applications like robots and autonomous driving need strong security. Reliability: Transmissions with a success rate of up to 99.99999% are required for cooperative autonomous driving and industrial automation[20].

4)Prioritization: To guarantee that vital data is sent with the maximum level of dependability, the network must prioritize streams according to their criticality[21].

All things considered, 6G seeks to overcome existing constraints and make advanced applications possible by achieving notable gains in latency, dependability, connection, and data rates.

Augmented Reality And Virtual Reality

The broad adoption of video-over-wireless, a very data-intensive application at the time, was made possible by the development of 4G technology. The increasing demand for streaming and multimedia services has made it clear that more spectrum, including millimeter-waves, is needed to serve the increased capacity needed by 5G networks. More applications that need a lot of data have been made possible by this rise in capacity, particularly those related to augmented and virtual reality (AR/VR). AR/VR applications are predicted to put pressure on the 5G spectrum, just like video-over-wireless did for 4G, when they become more widespread. This change will need a system capacity greater than 1 Tb/s, which is far more than the 20 Gb/s goal that was originally established for 5G. Furthermore, due to latency concerns, compression is not practical for AR/VR because of the need for real-time user engagement. As a result, each user will need a data rate in the gigabit-per-second range [9].

V. SPECTRUM FOR 6G

The new generation of IMT will be built upon advanced technologies, with a critical reliance on beneficial spectral band selection. Key usage scenarios for 6G, such as high-accuracy ISAC, wide-area XR, and high-resolution holographic communications, necessitate high bandwidths of approximately 0.75 GHz, 1 GHz, and 1.1 GHz, respectively. To fully harness the capabilities of 6G, an additional 500 to 750 MHz of new spectrum is required, along with the re-farming of existing spectra from previous IMT systems. To support these novel techniques and usage scenarios, additional spectrum allocations for IMT systems are to be made during the World Radiocommunication Conferences 2023 (WRC-23) and 2027 (WRC-27)[10].

Following WRC-23, the spectrum allocations for IMT services have become clearer. The 3.5 GHz band (3.3–3.8 GHz) has been ratified across Europe, the Middle East, and Africa, marking a significant advancement for IMT systems. The 6 GHz band (6.425-7.125 GHz), previously identified as unlicensed, has now been allocated to licensed IMT globally, with global harmonization of technical conditions paving the way for expanded mobile capacities. The 10–10.5 GHz band has also been assigned to IMT in North and South America, although with restrictions to protect adjacent services like the Earth-exploration satellite service. This band is intended for micro-cell base stations, with limitations on maximum equivalent isotropically radiated power and total radiated power[11].

Notably, WRC-23 allocates spectrum to IMT services without specifying a wireless generation, allowing some countries to utilize these bands for 5G-Advanced. Additionally, bands such as 470–694 MHz and 4800–4990 MHz, already identified for IMT in some regions, are now adopted more broadly. The agenda for WRC-27 includes consideration of future networks and their supporting bands, with studies planned for the 4400–4800 MHz, 7125–8400 MHz, and 14.8–15.35 GHz ranges to determine potential new IMT allocations[11].

Spectrum allocation is a global issue involving many stakeholders. Harmonization of the 6G spectrum and standards is critical for the success of 6G.

CONCLUSION

The advancement and implementation of 6G technology in the telecommunications and connectivity industry heavily rely on cutting-edge technologies and strategic spectrum assignments. Key usage scenarios for 6G, such as high precision ISAC, wide-area XR, and high-definition holographic communications, necessitate substantial bandwidths and fresh spectrum assignments to fully unlock their potential. The determinations taken at the World Radiocommunication Conferences (WRC) in 2023 and 2027 are pivotal in shaping the future of IMT services and facilitating the transition to 6G networks. recent spectrum assignments for IMT services, such as the endorsement of the 3.5 GHz band across Europe, the Middle East, and Africa, and the global assignment of the 6 GHz band for licensed IMT services, showcase progress towards expanding mobile capacities and enabling innovative technologies. The allocation of spectrum without specifying a wireless generation allows countries the flexibility to utilize these bands for both current and future technologies, including 5G-Advanced and potentially 6G.Looking forward to WRC-27, the consideration of additional bands for future networks and IMT assignments highlights the continuous evolution of telecommunications infrastructure. Global harmonization of spectrum and standards will be crucial for the successful integration of 6G technology and ensuring seamless connectivity worldwide. Collaboration among stakeholders will be essential in addressing the complexities of spectrum allocation and advancing the capabilities of 6G networks for the betterment of society. As we approach a new era in telecommunications, the transformative potential of 6G technology holds the promise of reshaping connectivity and revolutionizing various aspects of our daily lives. The strategic allocation and harmonization of spectrum bands, as emphasized through critical decisions at WRC-23 and the forthcoming WRC-27, are vital for unleashing the full potential of 6G. With anticipated applications spanning from high.

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