6th Generation Wireless Spectrum Applications, Opportunities and Challenges

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Manuscript received August 20, 2024; revised October 13, 2024; accepted January 14, 2025; published April 11, 2025

Abstract*—The introduction of the 6th generation spectrum presents opportunities for technology firms, entrepreneurs, and start-ups to develop innovative applications, services, offerings, and business models for experimental purposes, such as regulatory sandboxes, which encourage experimentation and the development of cutting-edge technologies and services. The result promotes the growth of the digital economy and improves economic competitiveness, all of which will contribute to economic expansion. These advancements encourage digital transformation in various industries, increase productivity, and present novel commercial opportunities. This paper thoroughly examines the potential influence of future innovations on the spectrum, like architectural frameworks, network management, new emerging techniques in the 6G spectrum, future spectrum challenges with associated solutions, efficient regulatory frameworks, the impact of Artificial Intelligence, Machine learning, and other emerging technologies. Furthermore, it examines potential challenges for domestic and global networks deployed in future generations. Moreover, it delves into the transformative opportunities and challenges of the 6G wireless spectrum, with a particular emphasis on the enhanced spectrum sharing that is facilitated by cognitive radio technologies, advanced protocols such as IEEE 802.22, IEEE 802.15.4 IEEE 802.1AE, and so on. These advancements enable the optimal utilization of frequency bands by enabling Dynamic Spectrum Access (DSA) and efficient resource management. By effectively balancing these opportunities with security considerations, 6G networks may unlock new applications across diverse sectors, which will pave the way for a more connected and efficient future.

***Keywords*—6G mobile technology, spectrum, spectrum-sharing, opportunities, challenges, applications**

I. Introduction

The advent of the 6G technology signifies an important breakthrough in communications, providing a chance to achieve unparalleled connectivity with exceptional speed, reliability, and future potential. Industries are expecting the significant potential and innovative prospects of 6G technology. Despite its remarkable ultra-low latency and extensive data processing abilities, it poses significant challenges. Establishing the 6G networks will require significant infrastructure expenditures, including advanced antennas and highly distributed networks of small cells. Moreover, it is essential to emphasize the security and privacy of data transmitted through these networks. This demands the implementation of robust encryption and authentication protocols. Fig. 1 illustrates a current spectrum of prospects based on available literature, significant challenges, and numerous applications of 6G technology.

6G wireless networks, which are on the horizon, will transform communication by incorporating cutting-edge technologies centered on artificial intelligence, sensing, and machine learning. These networks aim to facilitate extremely fast data speed, potentially surpassing terabits per second (Tbps), allowing the transmission of vast amounts of data in real-time. Such abilities are essential for applications that require considerable data transfer and rapid communication. These characteristics make them very suitable for applications that require fast response, such as driverless vehicles and remote medical treatments. The high reliability of 6G ensures uninterrupted and reliable communication, which is essential for applications that are key to the success of a mission. The development of 6G will profoundly influence Extended Reality (XR) technologies, encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). 6G's high data speed and low latency will facilitate immersive XR experiences. Wireless brain-computer interfaces are an innovative application that will use the high-speed and low-latency transmission of 6G, enabling real-time communication between the brain and external devices, possibly transforming sectors such as neuroprosthetics and human enhancement.

6G technology will provide substantial advantages to autonomous vehicles. The low latency and exceptional reliability will provide real-time communication between cars and infrastructure, enhancing safety and efficiency. Nevertheless, the ever-changing and complex nature of the 6G ecosystem presents major challenges to security and privacy. To guarantee the accuracy and authenticity of data in this environment, it will be necessary to employ cutting-edge technologies like Machine Learning, Deep Learning, Artificial Intelligence, and Blockchain. These technologies will have a pivotal role in identifying and reducing security risks and ensuring the security and confidentiality of data [1–9]. 5G networks are currently facing challenges in handling the growing volume of data traffic, adversely affecting service performance and processing capacities. On

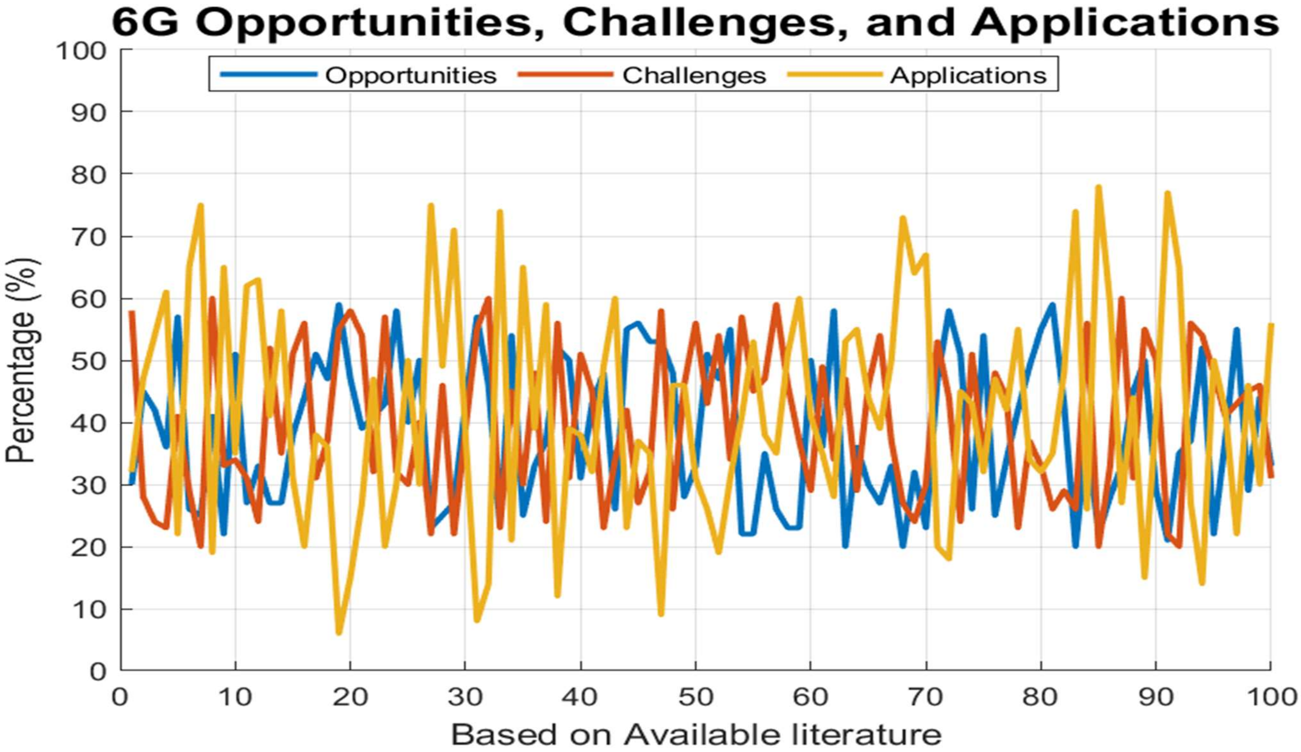

Fig. 1. 6G Opportunities, challenges, and applications based on available literature.

the other hand, 6G technology is being designed to address these problems by focusing on applications such as Industry 5.0, which focuses on finding solutions to the complex nature of hardware, enhancing the efficiency of transmitting data, and tackling social challenges that hinder the broad implementation of these solutions [10]. 6G features high-speed connectivity optimized for multiple devices, even in difficult circumstances [9]. The rollout of 6G technology boosts vehicular communication by reducing latency, vital for the seamless operation of real-time applications such as autonomous driving. Identification of threats and securing data with machine learning, deep learning, artificial intelligence, and blockchain technologies solve security and privacy challenges. In 6G's Internet of Everything (IoE) architecture, authentication and encryption secure network participation and user privacy [11]. Technological breakthroughs tackle issues such as transmitting vast amounts of data in remote locations and the requirement for fast connectivity. These technological improvements are essential for facilitating data-intensive applications and enhancing automation and communication in several industries, including the textile business. Expanding on the fundamental advancements of both 5G and 6G plays a role in improving textile automation and production by utilizing improved connectivity and efficient data management. This advancement benefits industries by facilitating real-time monitoring and control, streamlining manufacturing processes, and minimizing operating expenses [12]. The 6G technology will provide significant progress with data speed of 1 Tbps and latency of less than 1 ms, effectively dealing with issues related to hardware complexity, channel optimization, network architecture, and social implications. Artificial intelligence and machine learning are crucial in improving wireless networks, allowing for the development of advanced technologies. These advancements greatly enhance automation and communication roles, especially in rural areas where connectivity is crucial for economic progress and advancement [13]. Large-scale antenna arrays are expected to play a major role in satisfying the demanding needs of future 6G communications at the physical layer. These arrays facilitate high-performance functionalities such as extremely fast data transfer rate, low latency, and minimum communication delay. A significant outcome is that upcoming 6G networks might function within antennas' radiating near-field (Fresnel) area. The proximity provides distinct possibilities for improved performance but poses challenges regarding antenna design, signal propagation, and interference management [14]. Zero trust architecture and AI/ML applications are being investigated and implemented in 6G initiatives. These improvements aim to boost network security, privacy, and efficiency. However, achieving this balance is difficult, especially regarding security and privacy [15]. To meet the growing demand for fast data transfer and ubiquitous connectivity, scientists are studying Free-Space Optical (FSO) communication. This study proves that an FPGA-based FSO communication prototype is achievable. It shows how video signals can be sent over long distances in turbulent conditions and high wind speeds [16]. AI-powered 6G networks are ready to revolutionize smart cities [17–19] by seamlessly incorporating Internet of Things (IoT) AI, big data [20–22], blockchain [23, 24], and edge-cloud computing [25–27]. This integration fulfills the demanding Quality of Service (QoS) and Service Level Agreement (SLA) criteria. By leveraging these technological breakthroughs, 6G will provide reliable and efficient connectivity, empowering advanced urban administration and raising the standard of living in intelligent cities [28]. Future 6G mobile networks will encounter difficulties providing multicast, an essential feature for IoT and extended reality applications, such as teleportation. Non-Terrestrial Networks (NTNs) are crucial in this context because they expand worldwide mobile connectivity beyond the boundaries of physical networks. The present study investigates how the distinctive characteristics of NTNs can be utilized to provide efficient multicasting in 6G by addressing the special needs and overcoming potential challenges [29]. This study investigates the wireless communication systems operating within the frequency range of 100 GHz to 3 THz. subsequently focuses on analyzing the technical difficulties and potential advantages of the development of 6G networks. The work presents techniques for communicating over long distances, enhancing the performance of antennas, and optimizing beam steering. Additionally, it covers the latest advancements in propagation models and regulatory changes. The objective is to establish a highly interconnected society in the 6G era, characterized by extensive and high-speed 3D connectivity. The process will involve resolving coverage limitations and tackling social issues such as the digital divide and educational inequality. Ultimately, the aim aims to stimulate additional research and expedite progress in 6G technology [30, 31]. This study aims to tackle issues faced by 6G networks by prioritizing the optimization of the entire communication process to achieve superior data rate, low latency, remarkable reliability, and extensive connectivity. The work emphasizes the significance of technologies like enormous intelligent surfaces, ultra-massive MIMO (Multi input Multioutput), smart surroundings, and semantic communications in encoding information efficiently with context awareness. Furthermore, research investigates new approaches to communication, such as optimizing entire systems and combining machine learning with non-linear signal processing. The ultimate goal is to reconstruct the theoretical basis of communications [32]. Security threats will be most challenging in 6G IoT as were in 5G [33]. Table 1 presents a concise overview of research conducted on 6G applications, opportunities, and challenges. It emphasizes the steps being taken to tackle these challenges while making use of new technical breakthroughs to create an interconnected community.

Table 1. Summary of related work 6G developments, challenges, and opportunities

Author	**Application**	**Opportunities**	**Challenges**	**Major Contribution**
[2]	✓	✓	✓	Vision, requirements, enabling technologies, key drivers, and performance requirements.
[3]	✓	✓	✓	6G developments, enabling technologies, applications, and technical challenges.
[4]	✓	✓	✓	6G vision, enabling technologies, technical challenges, opportunities, key drivers, user cases, usage scenarios, requirements, Key Performance Indicators (KPIs), architecture, and enabling technologies
[6]	✓	✓	✓	6G vision, enabling technologies, challenges, and network architecture.
[7]	✓	✓	✓	6G development, challenges, key drivers, ubiquitous mobile ultra-broadband, ultra-high speed-with-low-latency communications, and ultrahigh data density.
[9]	✓	✓	✓	6G system: visions, drivers, requirements, architecture, usage scenarios. Opportunities, advantages, challenges, and research directions.
[10]	✓	✓	✓	6G security and privacy challenges.
[11]	✓	✓	✓	6G opportunities, challenges, applications especially security and privacy concerns.
[12]	-	✓	✓	6G challenges like huge data transmission.
[13]	✓	✓	✓	6G challenges, application, improvements.
[14]	✓	✓	✓	6G opportunities, challenges near field communication and applications.
[15]	✓	✓	✓	Architectural challenges of 6G.
[16]	-	✓	✓	6G Free space optical communication.
[28]	✓	✓	✓	Self-learning for AI application for 6G towards Smart Cities.
[30]	✓	✓	✓	Comprehensive overview of 6GApplications, opportunities, and challenges Above 100GHz.
[32]	✓	✓	✓	6G Challenges like intelligent surfaces and semantic communications.
[31]	✓	✓	✓	6G wireless networks hyper-connectivity.
[34]	✓	✓	✓	6G key technologies future communication requirements.
[35]	✓	-	✓	6G architecture.
[36]	✓	✓	✓	Comprehensive overview of applications, opportunities, and challenges.
[37]	✓	✓	✓	Comprehensive information about 6G technologies.
[38]	✓	✓	✓	Comprehensive information about 6G technologies.
[39]	✓	✓	✓	Comprehensive view about 6G technologies.
[27]	✓	-	✓	6G application scenarios on Micro/Nano Machines.
This paper	✓	✓	✓	6G spectrum application, opportunities, and challenges.

This research on the 6G wireless spectrum is essential for facilitating ultra-high data rate (up to 1 Tbps), extensive connection (accommodating 10 million devices per km²), and ultra-low latency (sub-millisecond). Investigating the integration of AI, machine learning, and innovative solutions will tackle issues such as intricate resource allocation and user privacy while optimizing the capabilities of 6G applications in smart cities and IoT. Comprehending these dynamics is crucial for formulating resilient frameworks and protocols to improve efficiency and security in forthcoming wireless networks.

Understanding and addressing the spectrum challenges associated with 6G networks is crucial to fully utilize the advancements in wireless communication. Spectrum development and management are essential to efficiently allocate and utilize frequencies to achieve the ambitious objectives of 6G, which include high data rate, low latency, and widespread connectivity. The industry is dealing with substantial unresolved issues concerning spectrum, including the optimization of spectrum usage efficiency and the mitigation of interference. These challenges are vital for maximizing the efficiency and reliability of 6G networks. In addition, it is crucial to investigate the architectural frameworks of the 6G spectrum, terahertz communications, and Free-Space Optics (FSO). These technologies present promising solutions for overcoming physical constraints in data transmission, potentially transforming communication capabilities in 6G. Their incorporation prompts concerns regarding the efficient implementation and expansion of these technologies to fulfill the requirements of forthcoming applications. Furthermore, comprehensive research on optimized spectrum management's social and economic advantages is required. Effective spectrum policies promote economic growth by encouraging innovation, addressing digital inequalities, enhancing social connectivity, and improving overall quality of life. This study aims to provide in-depth knowledge about the 6G spectrum and technologies, assessing their advantages, challenges, and areas that require enhancement. This paper will also help to identify research gaps to help the researcher focus their efforts on areas where there is a need for further investigation and to develop innovative solutions to address the challenges. This study aims to identify research areas that have not been explored in the 6G spectrum. Which also provides insights that can inform policy decisions related to the future spectrum. The primary goal is to focus future studies on these areas to describe innovative solutions for current challenges. What are the current challenges in developing the 6G spectrum, architecture, network management, and policy decisions? The rest of article is structured as section II 6G spectrum, section III: industrial challenge, section IV: architecture framework and network management section V: 6G applications, and section VI finally the conclusion.

II. 6G Spectrum

Standardizing the spectrum is one of the biggest challenges that current 6G technologies must overcome. As it becomes harder to identify a spectrum that can be assigned without interruption and utilized for mobile communications, the existing regulatory procedure for allocating a new spectrum for mobile services is time-consuming and complicated. To avoid a spectrum crisis that may thwart the economic benefits and growth associated with the increased use of mobile communication, authorities are advised to consider novel ways to address this trend. Future-focused spectrum policy and sharing are gaining traction as evolutionary enablers for future mobile communication systems. The growth of mobile networks and data is the primary driving factor for estimating the genuine demand for spectrum. The solution may be found in Fig. 2.

The management of spectrum in the context of 6G technology is developing to accommodate various access paradigms, such as licensed, unlicensed, and shared access approaches. Having a license spectrum remains essential to ensure operators have exclusive rights and can provide high-quality service guarantees when implementing high-capacity applications in 6G networks. At the same time, unlicensed spectrum, like Wi-Fi bands, is crucial for diverting traffic and providing affordable connectivity solutions for a wide range of consumer devices. License sharing, facilitated by dynamic spectrum access technologies, is a growing trend that allows multiple users to access spectrum bands based on demand. This strategy maximizes efficiency and spectrum utilization. The spectrum management framework in 6G seeks to achieve a harmonious equilibrium between the demand for dependable, high-performance services and the adaptability to accommodate various applications and emerging technologies such as IoT, AI-driven networks, and ultra-low latency applications. As the development of 6G networks progresses, it will be essential to optimize spectrum management strategies to meet the increasing need for connectivity and to promote innovation and economic growth in different industries.

Spectrum management controls radio frequency usage to promote effective utilization and provide a net societal benefit. Due to technical advancements in services and the quick growth of wireless internet service, demand for mobile internet, internet services, and wireless broadband services has skyrocketed. The description of the low, medium-, and high-band spectrum is dynamic and will continue to expand with time. The more profound significance might develop when new techniques, methods, and strategies emerge for overcoming very complex physical barriers, such as using terahertz communications or free-space optics in certain circumstances. Like all the nation's resources, the radio frequency spectrum may be used countless times. Planning new spectrum laws is crucial for international licensing policy. Since mid-band and high-band frequencies need a more robust and dense cellular connection. Several stages and parameters for the progress of new or improved spectrum are presented for developing and deploying future generations' spectrum for the forthcoming generations in Figs. 2–4. Figs. 3 and 4 describe the future spectrum deployment and management concept.

Managing the allocation and utilization of the 6G spectrum is a crucial component of upcoming mobile communication systems. The primary goal is to meet the growing need for higher data rates and network capacity [40, 41]. To ensure optimal use and meet the increasing demands of smart cities and IoT applications, efficient sharing of spectrum systems is essential during the transition to 6G networks [42]. To meet the demanding performance needs, the development of 6G technology will necessitate a substantial expansion in bandwidth, which will consequently pose issues related to the limited availability of radio frequencies [43].

Novel ideas such as Full-Spectrum Wireless

Communications (FSWC) have been suggested to make use of the full spectrum of electromagnetic waves, spanning from microwave to ultraviolet light, to offer ample bandwidth and facilitate novel communication models. Efficiently managing the distribution of spectrum resources on a global scale, taking into account technological factors and country-specific requirements, would be essential for the successful implementation of 6G networks. 6G networks encounter spectrum issues primarily related to limited availability, signal disruption, and the necessity for effective sharing methods. Intending to achieve enhanced connection, reliability, and minimum delay, the scarcity of available spectrum becomes increasingly critical, particularly as players transition to terahertz bands in 6G technology [44]. To address these challenges, novel technologies like New Radio Unlicensed (NR-U) in unlicensed spectrum and spectrum sharing between aerial/space networks and ground networks are being explored. Centralized Deep Reinforcement Learning (CDRL) and federated DRL (Deep Reinforcement Learning) frameworks are developed to optimize Ultra-Reliable Low-Latency Communication (URLLC) transmission in NR-U and Wi-Fi coexistence systems, enhancing reliability while ensuring fairness. Additionally, the proposal of an end-to-end layered SLA architecture leveraging Distributed Ledger Technology (DLT) and smart contracts aims to make SLAs more dynamic, transparent, and automated to meet the diverse requirements of critical applications in 6G networks. These approaches collectively aim to optimize spectrum usage and address the challenges faced by 6G networks as described in Table 2.

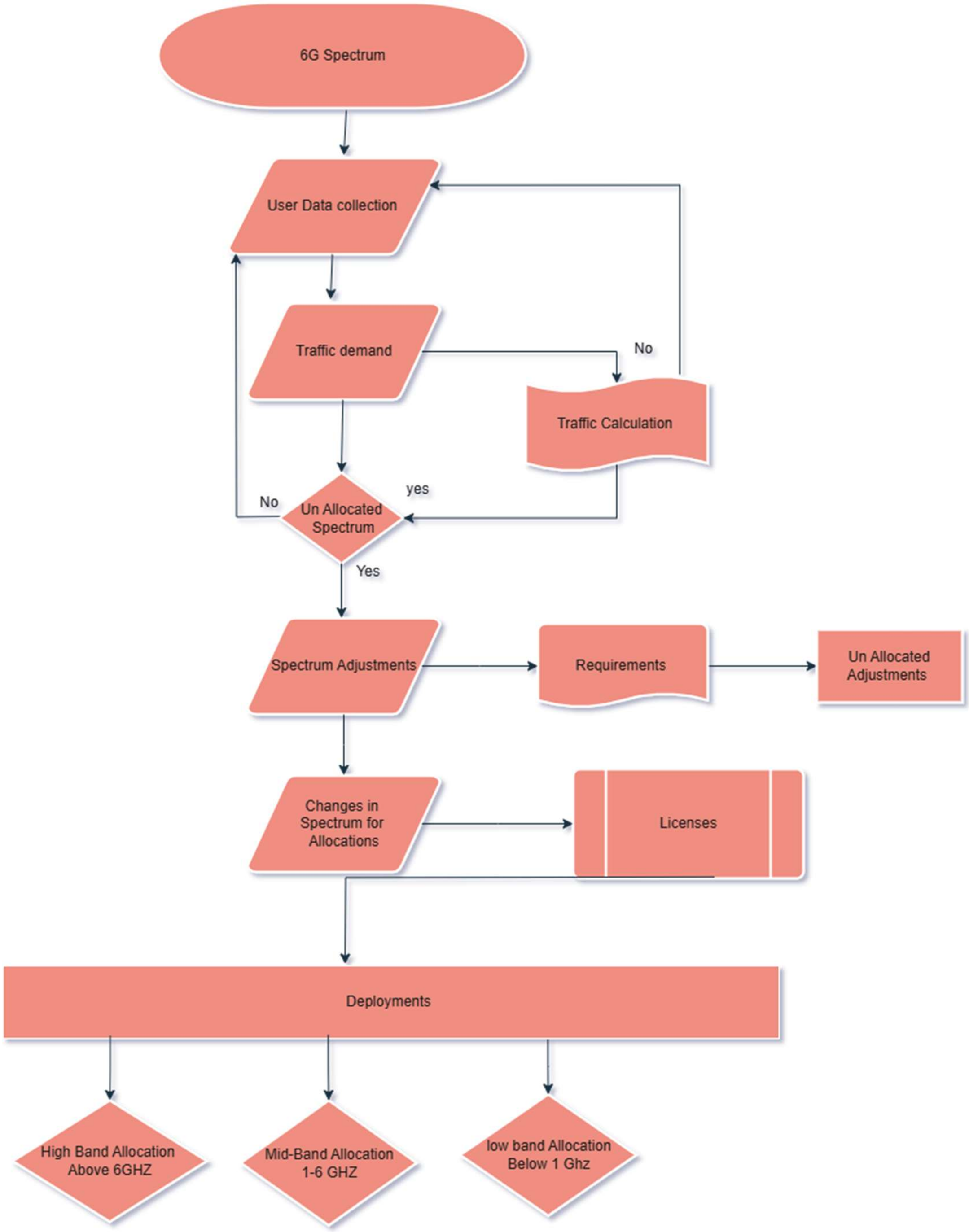

Fig. 2. 6G new spectrum allocation concept.

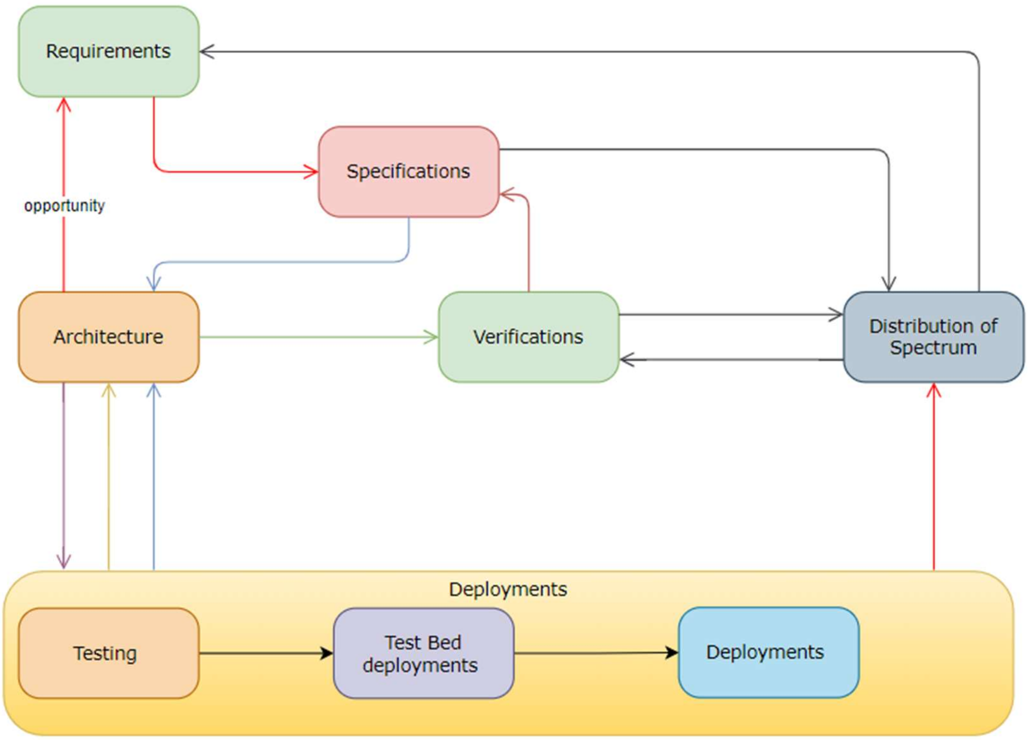

Fig. 3. 6G spectrum deployment concept.

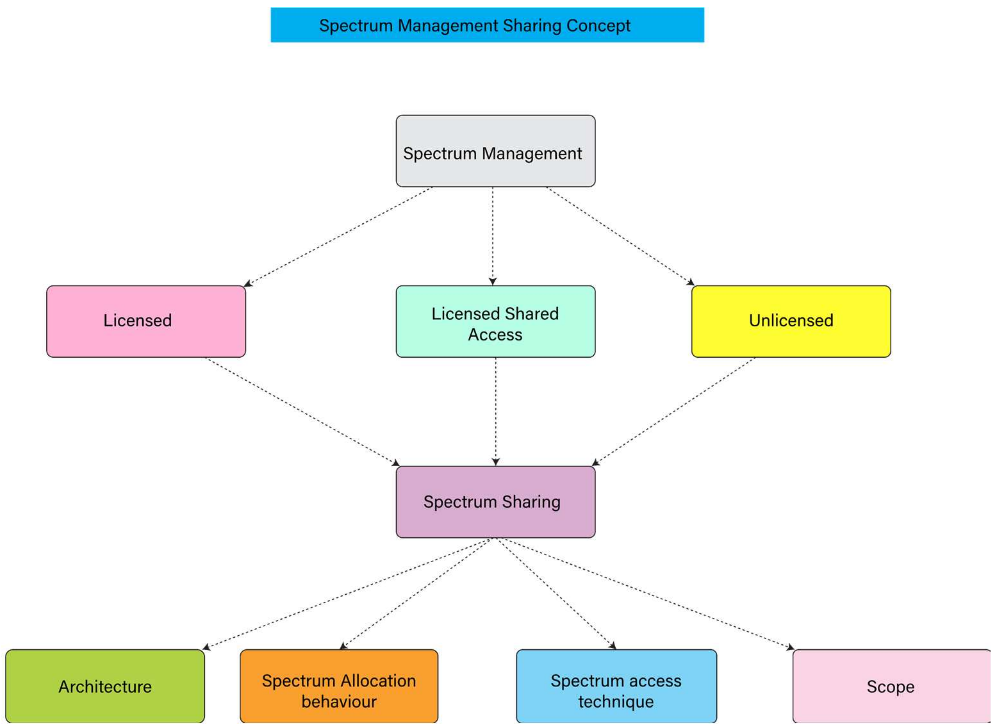

Fig. 4. 6G spectrum management concept.

Table 2. Challenges describe in literature

Autor	Method	Contribution	Challenges
[44]	Centralized Deep Reinforcement Learning (CDRL) employs a single agent to learn policies for all agents, while Federated Deep Reinforcement Learning (FDRL) distributes learning among multiple agents without centralized control.	CDRL and FDRL frameworks optimize URLLC transmission in NR-U, with CDRL improving NR-U reliability at the expense of WIFI reliability.	Interference and collisions among multiple radio access technologies sacrifice WIFI system reliability in the CDRL framework.
[45]	Optimizes UAV deployment height and transmitter power for communication rate. Improved Weber algorithm optimizes 3D position and power distribution of UAVs.	integrated space-air-ground network for seamless global communication coverage. Studies spectrum sharing between aerial and space networks with ground networks.	Mobility poses challenges for aerial and space networks. Fast sensing methods are essential for spectrum sharing with ground networks.

[46]	ML Algorithm for DSA, Physical layer based Distributed selection for Sub channels	ML Algorithm for spectrum sharing Which enables sub channel selection and Sub channel choices	Spectrum sharing between Licensed and Unlicensed Spectrum
[47]	Assessment of key trends and drivers of mobile communication by Co-ordination and developing innovation driver with international mobile communication strategy	Assessing trends and drivers of new mobile communication systems and coordinating the development of innovative drivers with international strategies.	Co-ordination challenges for 6G Spectrum
[42]	HetNet Spectrum Management	SDN enables dynamic 6G network coordination. Smart contracts streamline HSA for 6G HetNet spectrum.	Energy Cost because of high speed Network, Technology complexity for service agreement
[48]	Monte Carlo simulations for predicting radio wave propagation.	Estimate interference probability in 6G mmWave systems (26–71 GHz) using Monte Carlo simulations by modeling channel conditions and network architecture.	Terrain elevation modeling crucial for accurate interference probability estimation via Monte Carlo simulations in 6G mmWave systems (26–71 GHz).
[49]	Unified Non-Orthogonal Waveform (uNOW) facilitates flexible Time-Domain Channel Estimation (TD-CE) methods like NCP/UW and FDSS for waveform enhancement.	DFT-s-OFDM, flexible Time-Domain Channel Estimation (TD-CE) methods supporting Unified Non-Orthogonal Waveforms (uNOW).	non-linearity of Power Amplifiers (PA), compounded by the absence of a unified framework encompassing all enhancement schemes.
[50]	spectrum plan for 6G involves introducing Spectrum Chain, a blockchain-based dynamic spectrum-sharing framework.	introduction of Spectrum Chain, a dynamic spectrum-sharing framework based on blockchain technology.	Spectrum Chain, a dynamic spectrum-sharing framework based on blockchain technology.
[51]	Utilizing MIMO and NOMA techniques enhances multiplexing gain and capacity, while leveraging mmWave and THz channels maximizes communication capacity in 6G networks.	MIMO and NOMA techniques enhance multiplexing gain and capacity, leveraging mm Wave and THz channels to achieve higher communication capacities in 6G networks.	Advanced mmWave and Terahertz schemes meet diverse rate needs with varied BS caching, utilizing mMIMO/NOMA for enhanced 6G capacity, alongside ASCS for optimized HetNet caching integration.
This paper	Review of Spectrum management challenges	Spectrum management challenges	Architecture, network, industrial challenges

III. Industrial Challenges

Policy-based spectrum access determines which radios are allowed to receive the broadcast, including but not limited to the amount of time authorized, the frequencies that may be used, and the geographic locations where it can be received. This decouples spectrum access control policies and policy processing components from the radio platform. The "Policy Reasoner (PR)," a reasoning engine that makes up the policy framework, maybe in charge of enforcing, assessing, and carrying out the policies and resolving any disputes that may develop due to those actions. Because 6G spread will be significantly influenced by spectrum management strategy to provide a more effective spectrum, it can be viewed as a temporal need. Diverse parts of the world have developed their methods for introducing new radio spectrum. The competition for licenses to run 6G networks in the frequency ranges identified in the Radio Regulations (R.R.) as belonging to the terrestrial wireless service will begin among some government organizations. In the realm of 6G communication, several significant industrial challenges revolve around spectrum management and utilization. With the burgeoning demand for wireless connectivity and diverse applications, spectrum scarcity poses a critical hurdle.

Effective spectrum allocation and utilization techniques are essential to handle the wide range of services and the growing number of connected devices [52–54]. Furthermore, several technologies and services running in the same frequency bands require advanced techniques to reduce interference and strict spectrum-sharing rules. Millimeter wave frequencies, considered for 6G to achieve a high data rate, encounter challenges such as air attenuation and restricted coverage. To overcome these challenges, it will be necessary to develop advancements in beamforming, Massive MIMO (Multiple Input Multiple Output), and adaptive antenna technology. Furthermore, it is essential to create standardized international regulatory frameworks to ensure equitable spectrum distribution and effective interference management. Additionally, maintaining security and privacy in a connected environment remains a top priority. Addressing these obstacles will facilitate the practical application of 6G's capacity to revolutionize industries through the implementation of high-speed, dependable, and secure communication networks. Fig. 5 illustrates the challenges faced in the 6G spectrum.

The implementation and spectrum adherence have faced several challenges for mobile network operators, product developers, and industry standards bodies. There are numerous unresolved issues and challenges currently being encountered, which include:

Spectrum allocation and availability: the demand for spectrum frequently outpaces the supply, leading to a shortage of spectrum resources because there are often more requests for spectrum than available slots. The efficient and fair distribution of spectrum resources is a serious problem, especially in the face of conflicting demands from many stakeholders and businesses. Striking a balance between licensed and unlicensed spectrum, dealing with the problem of spectrum fragmentation, and ensuring there is enough spectrum available for future innovations are some continuing issues. Identification and allocation of new spectrum bands that can efficiently fulfill the changing requirements of new services and technologies.

Spectrum regularity framework: there is a lack of harmonization due to the disparities between different nations' and regions' legislative frameworks and procedures for allocating spectrum. Operators and product creators must navigate complex regulatory frameworks, licensing processes, and compliance requirements across several nations. These procedures can be expensive and time-consuming, which frequently impedes interoperability. Several factors, including the development of frameworks like dynamic spectrum access, cognitive radio, unlicensed spectrum utilization, spectrum sharing and dynamic access, offer difficulties in spectrum management. Developing effective sharing methods to seek optimal spectrum usage while guaranteeing equitable access for all users constitutes an ongoing challenge.

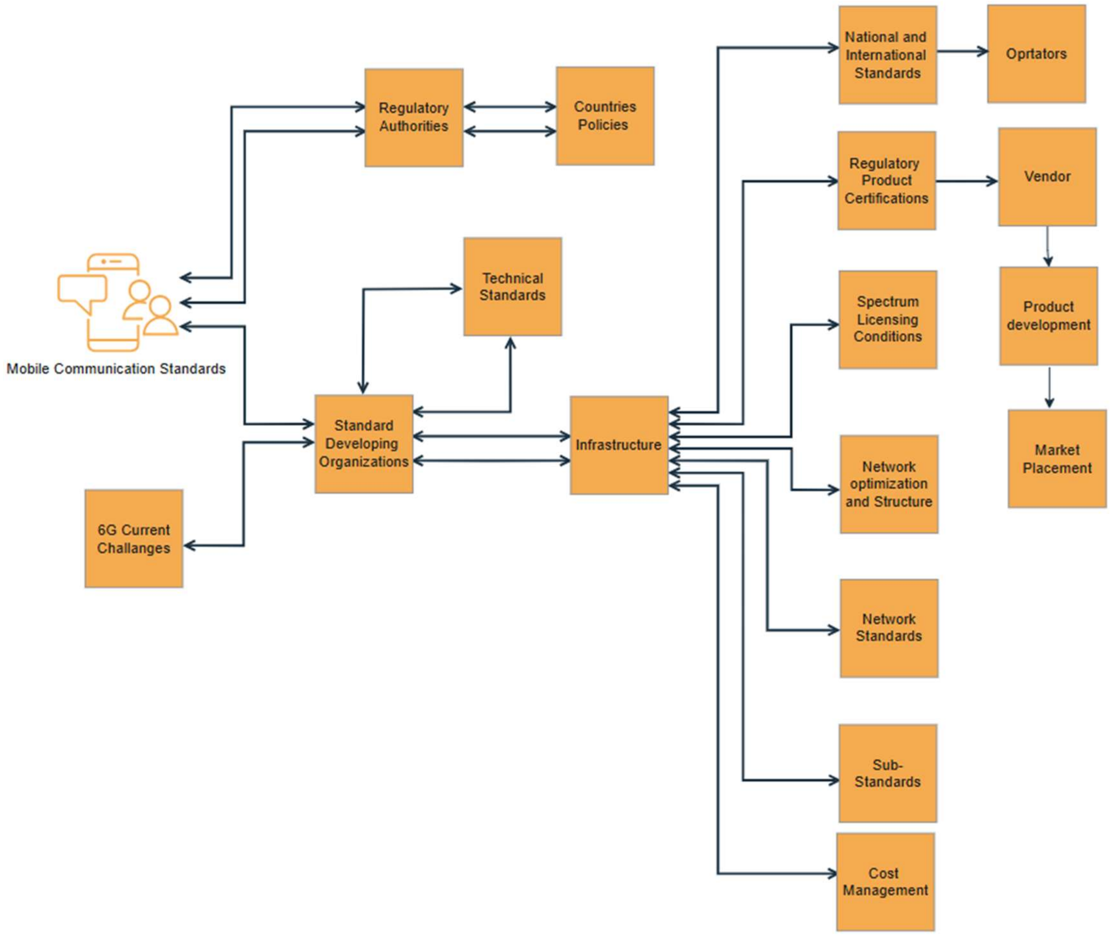

Fig. 5. 6G spectrum industrial challenges.

Spectrum auctions: purchasing licensed spectrum through auctions can have significant cost ramifications. Frequency auctions are a common technique of allocating licensed frequency. The ability of operators to invest in network infrastructure or provide cost-effective services may be hampered by high auction costs, especially for those with low resources. Finding a perfect balance between promoting government income collection and encouraging industry investment is difficult.

Coordination, interference, and harmonization: with more wireless equipment and services running in close proximity, coordination, and spectrum interference continue to be problems. Implementing efficient interference mitigation strategies, coordination mechanisms, and spectrum-sharing frameworks is necessary to manage and coordinate spectrum utilization across diverse technologies and users. These steps are essential to ensure effective cohabitation amongst various parties. International spectrum harmonization is highly significant in guaranteeing worldwide interoperability and providing smooth roaming capabilities. However, harmonization has several challenges because different nations have different agendas, regulatory structures, and national interests. Developing global coordination and collaboration among regulatory agencies is crucial to resolving these issues and achieving a standardized spectrum utilization. Technical standards, protocols, and spectrum access methods are principally responsible for the difficulties in creating seamless interoperability, spectrum sharing, and coordination across these many technologies.

Policy: A fundamental difficulty in spectrum policy and planning is developing efficient spectrum policies and planning strategies that keep pace with technology improvements and changing market needs. The speed at which policies are formulated and decisions are made is frequently outpaced by the quick rate of technological innovation. As a result, there is often ambiguity in regulatory issues and delays in the distribution and use of spectrum. Compliance with spectrum rules must be ensured by spectrum monitoring and enforcement. Particularly given the growing adoption of wireless devices and the constantly shifting spectrum use environment, identifying and resolving unlawful spectrum consumption, interference origins, and non-compliant devices can present considerable issues. Regulators, operators, and product developers have substantial difficulty in anticipating and resolving future spectrum requirements.

The spectrum deployment necessitates careful attention to technical requirements and considerations to achieve smooth integration and maximize performance. Here are several important factors to consider:

- For seamless integration and excellent performance, it's essential to ensure that user devices, network hardware, and infrastructure components support the necessary radio access technology compatibility.

- Antennas require being constructed or tuned to work effectively within the deployed spectrum's precise frequency range, considering antenna gain, radiation pattern, beamforming capabilities, and interference control techniques to maximize coverage and capacity.
- Identifying optimal cell sizes, optimizing cell location, changing transmit power levels, and configuring interference control strategies require proper RF planning and network optimization. For optimum performance, quality of service , capacity, and coverage characteristics may be optimized using RF planning tools and algorithms. Coexisting with current networks and limiting interference between nearby cells or neighboring networks is essential.
- High-speed, low-latency links are essential for meeting the demands of high data rates and low-latency requirements. Upgrading and expanding the backhaul and transport infrastructure is crucial to effectively managing the increased traffic volume and ensuring smooth integration and optimal performance.
- Spectrum deployments need precise network synchronization, particularly for technologies like 6G. Close synchronization between base stations and network components is crucial to support sophisticated capabilities like coordinated multipoint transmission and beamforming. Synchronization standards and procedures must be followed to ensure peak performance. Systems for monitoring, regulating, and optimizing the performance of next-generation spectrum deployments are required. These technologies enable proactive monitoring, fault management, performance optimization, and service delivery. Automation and clever algorithms may aid real-time optimization and effective resource allocation.
- Testing and validating network hardware, user gadgets, and infrastructure parts is crucial to guarantee compatibility and optimal operation end-to-end testing, interoperability testing, and performance benchmarking should verify that a product meets industry standards. Encryption, authentication, access control, and privacy-preserving measures are needed to protect network infrastructure, user data, and communication services. Resolving these issues requires constant collaboration between regulators, operators, industry stakeholders, and standards bodies. Spectrum rules must be implemented and observed efficiently through open communication, flexible policy, technical improvements, and international collaboration.

IV. Architectural Frameworks and Network Management

The architecture of a 6G network supports the more advanced communication needs of subsequent wireless technology. Network functions are managed and controlled by the core network. The core network's centralized core manages traffic routing and network operations. Distributed core nodes throughout the network handle localized traffic and provide edge computing.

Access Networks connect user devices to the core network. These access networks consist of various components, including Macro cells [55], Small cells [51, 56–58], and Massive Multiple-Input Multiple-Output (MIMO) [59–62] antennas. Macro cells cover massive areas, while small cells boost capacity and coverage in highly populated areas. Advanced beamforming improves spectral efficiency and data transmission rates in massive MIMO antennas.

Backhaul networks offer high-speed data transmission between the core network and access points. The main backbone infrastructure is high-bandwidth, low-latency fiber optic links. In remote or rural locations where fiber optic cables are difficult to deploy, microwave links complement fiber optics.

Edge computing improves network speed and enables low-latency services. Edge nodes, positioned at the edge of the network, provide decentralized processing capabilities and support the implementation of network slicing, allowing for the creation of virtualized network instances tailored to specific applications or services. In addition to terrestrial infrastructure, the architecture of a 6G network may incorporate satellite communication technologies. A satellite constellation composed of Low Earth Orbit (LEO) satellites interconnected via Inter-satellite links can provide global coverage and support low-latency communication, particularly in remote or mobile scenarios.

Ultimately, the architecture of a 6G network is designed to accommodate the growing demands for high-speed, low-latency communication while supporting a diverse range of applications and services across various industries.

The architecture of 6G networks describe in Fig. 6 will experience a substantial transformation compared to previous generations, including cutting-edge technologies to fulfill the requirements of extremely fast connection and a wide range of applications. The 6G design efficiently integrates core, access, backhaul, edge computing, and satellite communication technologies. Core networks will manage data flow and network connectivity as the hub. To boost coverage and capacity, access networks will leverage mm-wave, Massive MIMO, and sophisticated beamforming to connect end-users. Backhaul networks use fiber optics and combined terrestrial-satellite systems to efficiently transmit massive amounts of data between core and access networks. Edge computing will bring computational power closer to end-users and devices, enabling low-latency applications and data processing. In addition, satellite systems will expand the global coverage of 6G networks, ensuring widespread connectivity and supporting applications that necessitate extensive geographical reach. Collectively, these components create a resilient and unified 6G framework that is positioned to profoundly improve connectivity, facilitate upcoming technologies such as AI and IoT, and facilitate unparalleled levels of digital transformation across various industries. Fig. 7 describes efficient management of spectrum in 6G networks which will play a vital role in maximizing performance and meeting the diversified needs of advanced applications and services. 6G spectrum management will differ from previous generations by implementing a dynamic strategy to optimize utilization across a broad-spectrum range, encompassing both traditional sub-6 GHz bands and higher-frequency bands.

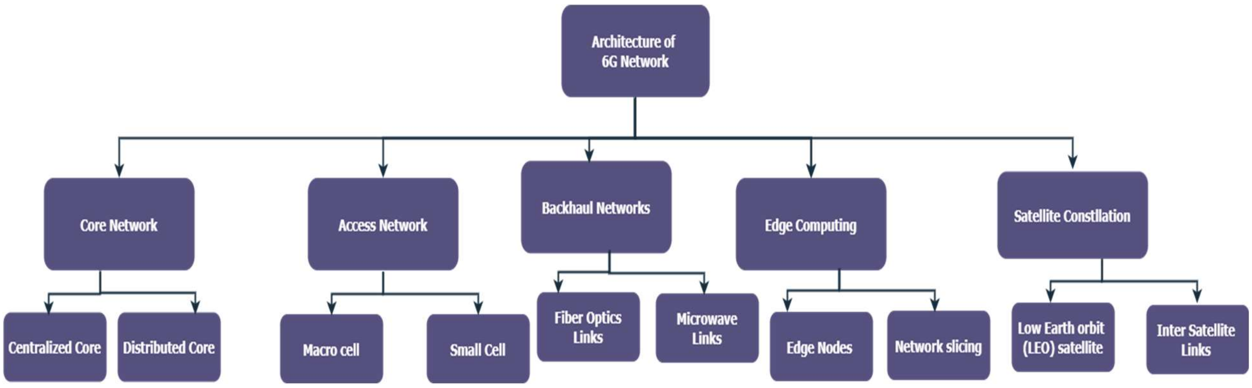

Fig. 6. Architecture of 6G network.

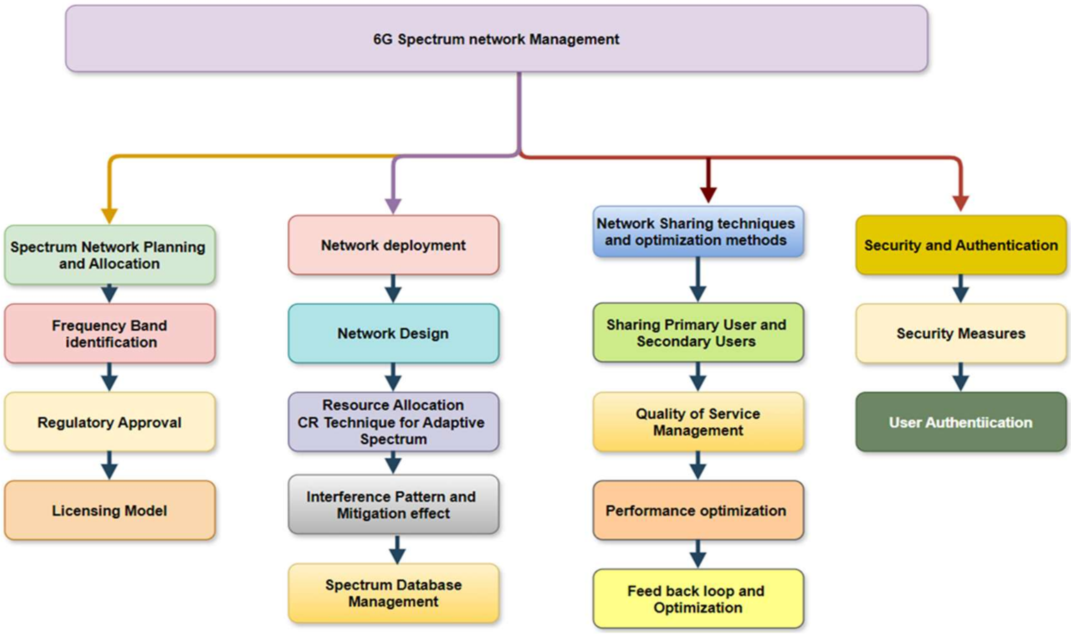

Fig. 7. Spectrum network management.

Utilizing advanced spectrum planning technologies would guarantee efficient allocation, hence improving network capacity and data rates necessary for applications such as ultra-high-definition video streaming and real-time gaming. The regulatory bodies will have a crucial role in determining appropriate frequency bands and creating licensing structures that promote equitable access and effective sharing of spectrum among multiple operators. The deployment strategies will prioritize scalability and robustness by utilizing small cell installations in urban areas and satellite technology for wider coverage. The security measures will incorporate strong encryption, secure authentication procedures, and AI-powered threat detection to protect data integrity and ensure users' privacy across networked devices and services. The primary objective of 6G spectrum management is to create a versatile, effective, and secure structure that caters to the varied requirements of forthcoming digital connectivity and applications.

Fig. 8 describes various innovative techniques and technologies that have emerged in efficient spectrum sharing and coexistence. Dynamic Spectrum Access (DSA), facilitated by cognitive radio approaches, permits Internet of Things (IoT) devices to exploit untapped spectrum bands when available. Advanced machine learning and artificial intelligence estimate spectrum use patterns and optimize spectrum allocation in real-time, improving this method. Spectrum management uses blockchain technology to secure share spectrum, and signal processing techniques improve spectral efficiency and reduce interference. By precisely targeting receivers, spatial reuse, and beamforming reduce interference. In congested spectrum situations, interference cancellation and spectrum sensing ensure connectivity. These efforts are supported by the spectrum sharing frameworks, which regulate spectrum access and IoT device interoperability. Multi-radio platforms use many radios to take advantage of spectrum diversity, while dynamic interference management adjusts transmission parameters in real time. Cooperative spectrum sensing helps several entities discover and avoid used channels. These approaches and technologies form a complete framework for spectrum sharing and coexistence in IoT installations.

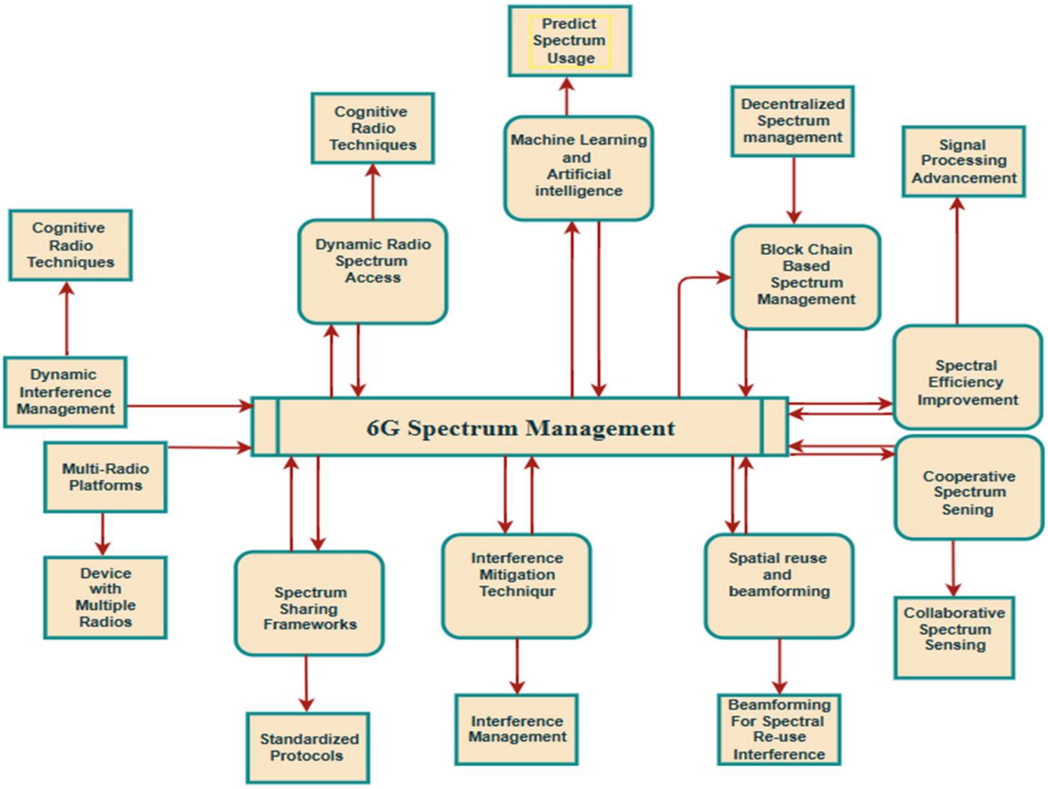

Fig. 8. New emerging techniques in 6G spectrum.

Dynamic Spectrum Access (DSA) manages interference and utilizes access opportunities. DSA interference management requires power regulation and beamforming. Power control optimizes transmission power levels in real-time to reduce interference with primary customers and maximize spectrum use while meeting regulatory standards. Beamforming is essential for directing radio signals to specific receivers, improving signal strength, and reducing interference. Opportunistic access in DSA requires spectrum sensing, which detects and uses underutilized spectrum. This strategy optimizes spectrum efficiency and capacity by allowing secondary users to use radio waves when prime users are not sending information. However, Static Spectrum Allocation (SSA) focuses on licensed spectrum as described in Fig. 9. Licenses, either through auctions or administrative distribution, give operators exclusive rights to frequency bands. Service providers innovate and compete with unlicensed spectrum because it offers wider access without exclusive rights. Leasing offers temporary spectrum access, giving users additional flexibility. Pooling in SSA is the systematic use of the spectrum according to schedules or standards. Pooling ensures interference-free operating in allotted frequency bands. The differences between DSA and SSA demonstrate the need for spectrum management variety in current wireless networks. DSA uses dynamic, opportunistic access and interference control, while SSA uses static spectrum allocation with licensed and unlicensed alternatives, leasing, and pooling.

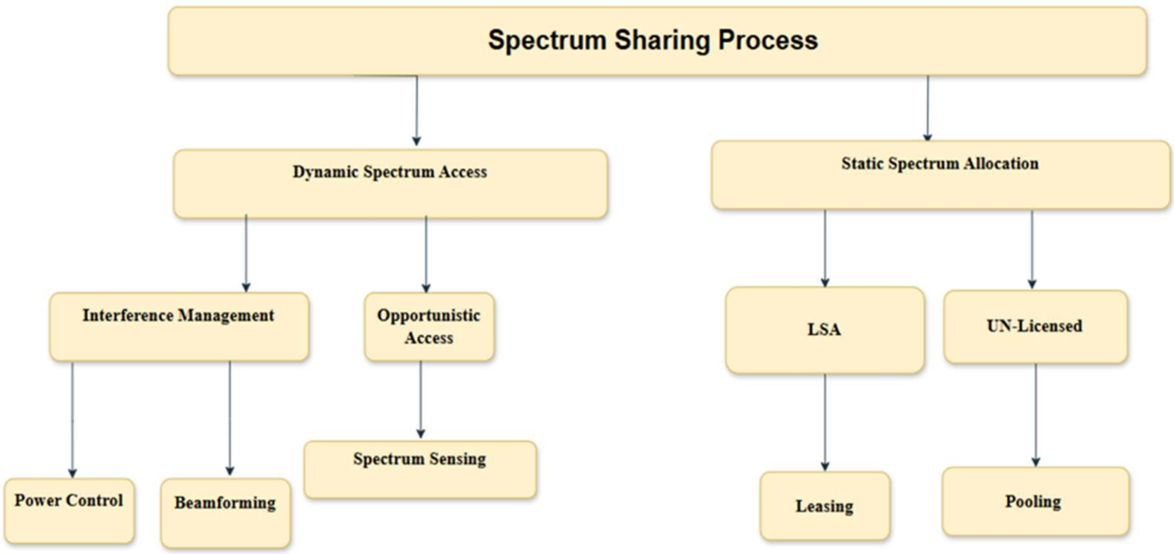

Fig. 9. Spectrum sharing process.

A. Dynamic Spectrum Access

Dynamic Spectrum Access (DSA) is an advanced way of regulating radio frequencies that allows for the adaptable and effective utilization of spectrum resources. It accomplishes this by dynamically allocating spectrum based on current demand and environmental circumstances. One of the main difficulties in DSA is the limited availability and effectiveness of spectrum, which requires the utilization of a restricted spectrum despite increasing demand. Interference control is crucial and requires the deployment of advanced signal processing techniques to reduce conflicts between different users. Regulatory and legislative frameworks must be flexible to enable dynamic allocation, which presents a further challenge. Moreover, it is crucial to guarantee the security and privacy of a shared spectrum environment to prevent illegal access and data breaches. The integration of technology and the compatibility between different devices and networks provide problems in establishing interoperability. Spectrum Database Management encompasses the creation of optimized databases and algorithms to effectively manage real-time spectrum availability and synchronization. To ensure the successful development and operation of DSA systems, it is crucial to tackle these problems. Fig. 10 describes the critical challenges of DSA.

Fig. 10. DSA challenges.

It is crucial since the growing demand leads to an increase in radio waves. DSA in 6G networks poses both difficulties and possibilities for future uses [63, 64]. The use of blockchain-based systems for spectrum allocation in 6G networks addresses concerns around fair distribution of spectrum and cooperation among telecommunications operators [16, 65–68]. This technique ensures both transparency and security in spectrum transfers, effectively preventing any unfair practices and ensuring a competitive environment. Furthermore, the use of Free-Space Optical (FSO) communication in 6G applications enables rapid data connections in networks with varied attributes and wireless backhauls, showcasing the potential for high data transfer rates and extensive connectivity [69]. FSO technology has the ability to significantly enhance the capacity and efficiency of 6G networks, effectively addressing the increasing demand for high-speed communication. The implementation of dynamic spectrum allocations in 6G networks, which provide improved stability, capacity, and flexibility, allows for the creation of innovative networked-in-a-box services and Internet of Everything applications. This emphasizes the significance of efficient dynamic spectrum access methods in upcoming 6G systems [70]. By utilizing these developments, 6G DSA has the potential to completely transform spectrum management, guaranteeing effective and transparent spectrum usage for a diverse array of developing wireless applications. The limited availability of spectrum in 6G networks has a significant effect on Ultra-Reliable Low-Latency Communication (URLLC) [71], connection establishment, service retainability [72], and network capacity for smart cities and IoT applications [73], which necessitates efficient spectrum management to enhance capacity and avoid underutilization [74]. It is essential to address scarcity by implementing intelligent spectrum sharing, introducing new frequency bands, and improving bandwidth reuse in order to fully utilize the capabilities of 6G. The integration of AI and federated learning in 6G networks requires comprehensive mechanisms to address threats such as fraud and privacy attacks, making security and privacy considerations crucial. The idea for 6G architecture, which integrates blockchain technology to boost security, prioritizes edge intelligence, specialized subnetworks, and reliable networking to facilitate a wide range of future applications [75, 76].

B. Un-licensed Spectrum

Research in utilizing unlicensed spectrum, particularly in the 6 GHz bands, has been sparked by the shift from 3G to

6G networks in order to address the increasing need for higher speeds and reduced latency [77, 78]. Millimeter waves have a substantial capacity, but their range is restricted because of the large amount of signal loss. The presence of this constraint gives rise to challenges, which is why the sub-6GHz spectrum is appealing for emerging cellular networks. In order to address the issues of coexistence amongst different wireless technologies operating in these frequency bands, it is essential to utilize innovative approaches such as power control techniques and adaptive channel sharing protocols. The aim of these procedures is to enhance the efficiency of data transmission, minimize disruptions caused by interference, and ensure equitable access for both cellular and WiGig users. The allocation of additional unlicensed spectrum in the 6 GHz frequency ranges offers opportunities for facilitating applications that necessitate substantial bandwidth. This emphasizes the significance of deploying suitable interference management measures to guarantee the effective utilization of the spectrum and uninterrupted functioning for all users. The key issues in Fig. 11 in unlicensed spectrum for 6G involve mitigating concerns regarding interference between various wireless technologies, improving spectrum sharing to cater to diverse requirements, and developing robust regulatory frameworks that ensure equitable access and efficient spectrum management.

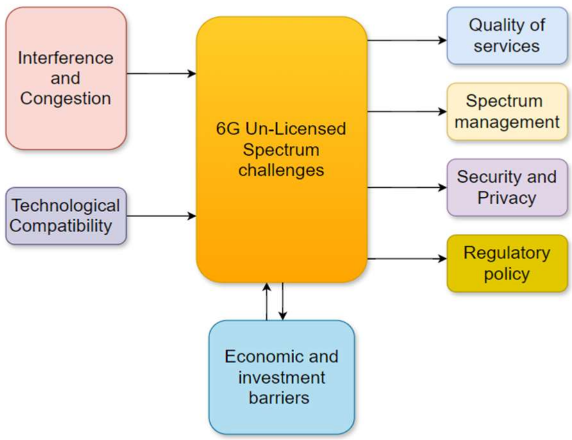

Fig. 11. Challenges in the un-licensed spectrum.

The following licensed, unlicensed, and licensed shared access spectrum constraints has been discussed based on available resources in Table 3.

C. Terahertz (THz) Communications and Free-Space Optics (FSO) Physical Limitations

Future generations of communication systems may be able to enhance their spectrum capabilities with Terahertz (THz) communications and Free-Space Optics (FSO). Compared to conventional microwave or optical communication systems, terahertz communications and FSO can offer a substantially larger bandwidth. High-speed and high-capacity communication networks are made possible by the broad spectrum accessible in the terahertz frequency range, which allows for the transfer of massive volumes of data. Both technologies offer very high data rates and are capable of multi-gigabit or even terabit-per-second transmission rates, enabling quick data transfer for applications requiring much capacity. Untapped spectrum resources exist in the terahertz frequency range, which may help ease the developing spectrum shortage in lower frequency bands. Communication systems may access unused spectrum resources by using terahertz frequencies, boosting the available bandwidth and meeting the rising demand for real-time communication. Compared to lower frequency bands used in urban areas, their distinctive propagation characteristic might be advantageous for high-density deployments that make them less sensitive to eavesdrop-ping and interference and for targeted communication demands. FSO eliminates the requirement for fiber-optic connections by enabling high-speed communication across free space. Using sophisticated beamforming and spatial processing techniques, these technologies may allow simultaneous communication between several users in the same physical space. These technologies make unlicensed spectrum utilization possible, allowing cutting-edge services and applications without expensive licensing processes and encouraging entrepreneurship and innovation. Accurate and consistent characterization of GHz and THz frequencies may be accomplished by establishing and standardizing measurement parameters and standards. To enable precise characterization and interoperability of next-generation spectrum, it is essential to harmonize measurement parameters and standards for gigahertz (GHz) and terahertz (THz) frequencies. There are many early-stage standards for terahertz and gigahertz, including frequency measurement traceable references, calibration methods, measurement tools, power characterization, sensor calibrations, measurement uncertainty, estimation techniques, measurement bandwidths, resolution bandwidths, noise floor specifications, dynamic range, modulation depth, modulation index, antenna characterization, radiation patterns, gain, and polarization.

Table 3. A detailed comparison view of spectrum licensed, unlicensed and licensed shared access

Limitations Spectrum	Licensed	Licensed shared access	Unlicensed
Spectrum access	Frequency assigned to the primary user	A hybrid license sharing on a specific frequency with a secondary user	Available without license
Advantages	Guaranteed access	Shared access. Increases utilization	Entry without a license, low barrier
Disadvantages	High maintenance and license cost	Need complex, which can reduce reliability for a primary user	Less reliable, opportunity access, interference, and congestion due to lack of regulations
Licensing authority	Government/regulatory body	Government/regulatory body	Not required
Cost	High cost	Lower than traditional	No cost

Availability	Limited to allocated organization	Shared availability	Without restriction available
Interference management	Licensed holders	Authorized users	Device and networks
Quality of service	Dedicated access, high quality	Shared access among users may be affected	Quality can be affected due to interference and congestion
Restriction	Certain standards or technologies	Fewer restrictions than in traditional	No restrictions
Innovation potential	Limited due to license restriction	Moderate due to sharing access and flexibility	Higher innovation potential due to no restrictions
Deployment	Limited	Limited	Unlimited
Frequency reuse	High-frequency reuse	Limited frequency reuse due to sharing	Limited frequency reuse due to interference
Security	Highly secure	Moderate secure	High risk due to open access
Flexibility	Limited	Moderate	Highly flexible
Coverage	Highest	High	Low
Capacity	Highest	High	Low
Privacy	High	High	Low
Category	Exclusive	Shared	Open
Regulatory compliance	Highest	High	Low
Efficiency	High	Medium	Low

Coexistence testing processes, standardized channel characterization, interference metrics, interference power measurement techniques, and interference mitigation plans. Despite the potential advantages of terahertz communications and free-space optics, specific technical issues still need to be resolved, including propagation loss, atmospheric attenuation, system complexity, and financial concerns. Even yet, further spectrum capability expansion and physical limits in the next generation of communication systems may be overcome with sustained research, development, and standardization activities in these areas. This enables the development of next-generation wireless communication systems and applications and fosters interoperability and practical spectrum usage. Wireless spectrum issues provide important challenges in the field of communications, driven by the finite nature of spectrum and rising demand for wireless services. Key issues described in Table 4 include spectrum scarcity, interference, fragmentation, expensive license prices, technology obsolescence, security concerns, environmental implications, and restricted availability in rural and underprivileged areas.

D. Future Spectrum Challenges and Associated Solutions

To address these challenges, a comprehensive strategy is required, including the implementation of advanced technologies such as cognitive radio and energy-efficient methods, the enforcement of regulatory reforms to reallocate spectrum and promote sharing, and the adoption of innovative practices such as flexible spectrum management and community-based networks. By implementing these techniques, the wireless sector may improve spectrum efficiency, provide higher service quality, and meet the rising demand for wireless communications, eventually sustainably driving innovation and connection.

Table 4. Future spectrum challenges and associated solutions

6G Spectrum	Future challenges	Solution
Spectrum scarcity	Finite resources	Spectrum reallocation, spectrum sharing, efficiency improvement
Interference	Performance and reliability	Advanced modulation and coding techniques, cognitive radio standards, regulation, and standard
Spectrum fragmentation	Insufficient for high-bandwidth	Spectrum aggregation, spectrum harmonization
High cost	Limited availability for small operators	Spectrum auctions with fair Access, unlicensed Spectrum
Technological challenges	Rapid advancements	Flexible spectrum management
Security and privacy concerns	Security and privacy issues	Encryption and authentication. regulatory oversight
Environmental impact	Energy consumption, electronic waste	Energy-efficient technologies and sustainable practice, green technologies, recycling programs
Spectrum underutilization	Underutilized,	Allocation to secondary spectrum. Or un allocated users
Quality of services	uncoordinated use	Upgradation of QoS protocols
Scalability	Artificial intelligence, big data, and cloud computing	AI-powered resources allocation, Analytics, scaling with cloud computing and distributed systems
Interoperability	API standards, middleware, and everyday communication protocols	Integration platforms, communications gateways and bridges, and standardization of protocol
Reliability	Recovery system, backup, and fault tolerance redundancy	Disaster recovery strategies, predictive maintenance, and continuous monitoring
Power management	Communication networks, energy-efficient sensors, and devices	Optimization of energy harvesting, renewable energy sources, and battery management
Complexity	Communication networks, energy-efficient sensors, and devices	Automated configuration, simplified application development tool, and user-friendly interface

E. 6G Resource Allocation and Management

Resource allocation and management in 6G will be critical to satisfy requirements for ultra-high data speeds (up to 1 Tbps), ultra-low latency (sub-millisecond delays), and extensive connectivity (up to 10 million devices per km^2), while also including terahertz (THz) frequency ranges (0.1–10 THz). Resource allocation and management in 6G employ protocols include IEEE 802.15.4 for low-power IoT networks, IEEE 802.22 for cognitive radio, and IEEE 802.11ax for enhanced Wi-Fi, in conjunction with methodologies such as Multi-access Edge Computing (MEC) and machine learning algorithms for predictive allocation. Supplementary standards like ETSI EN 303 345 provide dynamic spectrum access, improving resource management efficiency and capacity. Resource management and allocation in 6G networks encounter several problems, with advanced algorithms and artificial intelligence serving a crucial function. Porselvi presents the CORA-6G algorithm to optimize offloading in automotive networks, which improves efficiency by as much as 25% [79]. Ismail emphasizes the significance of AI in resource management for Cloud RAN in 6G, accentuating architectural enhancements [80]. Ramana introduces EvoNetSlice, which employs evolutionary algorithms for real-time resource allocation in network slicing [81]. Hui investigates multi-dimensional resource management in space-integrated ground access networks, tackling the intricacies of computing and wireless resources [82]. Yadav emphasizes cloud-assisted methods to improve performance in a dynamic context [83].

F. 6G Network Slicing

Integrating 6G network slicing entails utilizing advanced frameworks such as [84] strategic design for optimizing IoT in smart cities and [85] explainable deep reinforcement learning models for improved decision transparency. Furthermore, as suggested by [86], incorporating cybersecurity measures alongside optimizing reliability and multi-objective performance, as evidenced by [87], guarantees resilient and secure slicing capabilities. These integrated methodologies facilitate the attainment of scalable, secure, and dependable 6G network slicing.

6G network slicing will encompass sub-6 GHz, millimeter-wave (30–100 GHz), and terahertz (0.1–10 THz) frequency bands to address varied application requirements. Sub-6 GHz will provide mMTC with bandwidths ranging from 100 MHz to 1 GHz for IoT, and millimeter-wave segments will provide 1–10 GHz bandwidth for eMBB, achieving speeds of up to 100 Gbps. Terahertz bands will provide bandwidths of up to 100 GHz for high-capacity applications, resulting in data speeds of 1 Tbps. AI-driven dynamic spectrum sharing will enhance resource allocation, while NFV/SDN frameworks will ensure low-latency, high-reliability slicing for essential applications such as URLLC.

G. Impact of Artificial Intelligence, Machine Learning, and other Emerging Technologies

The use of AI and ML technologies in 6G networks will transform applications, including autonomous vehicles, Industry 4.0, and non-terrestrial networks, improving security, efficiency, and dynamic resource allocation [88–92]. Advanced AI-driven frameworks, serverless computing, and dynamic resource management are essential for managing the complexity and size of 6G networks. Furthermore, AI's function in security and industrial applications will tackle developing difficulties such as data privacy and adaptability [88, 93–96]. 6G networks, artificial intelligence, machine learning, and Mobile Edge Computing (MEC) will significantly enhance the optimization of wireless spectrum applications and the dynamic management of network slices. These technologies will meet future applications' complex demands like driverless vehicles, smart cities, and immersive Augmented Reality (AR)/Virtual Reality (VR), which necessitate extremely dynamic, low-latency, and high-bandwidth communication. Artificial intelligence will be integrated at several tiers of the 6G architecture, spanning from radio access networks to core networks, facilitating intelligent spectrum allocation, traffic forecasting, and resource optimization. AI-driven dynamic spectrum sharing would provide real-time bandwidth reallocation according to traffic patterns, optimizing spectral efficiency in contexts such as massive machine-type communications (mMTC), where IoT devices require differing connectivity levels throughout the day.

The influence of AI, ML, and novel technologies on 6G wireless spectrum applications is significant, facilitating intelligent resource allocation, real-time optimization, and improved user experiences across multiple industries. Essential technological standards comprise IEEE 802.11ax for sophisticated Wi-Fi technologies, ITU Radiocommunication Sector (ITU-R) M.2410 for performance criteria in 6G networks, 3GPP NR specifications for adaptable air interface management, and IEEE 802.15.4 for low-power IoT communications. Additional pertinent standards include ETSI EN 303 345 for low-power wide-area networks, IEEE 1900 for dynamic spectrum access and cognitive radio, and ITU-T Y.3100 for network design concerning artificial intelligence. Network operators are implementing open RAN principles to enhance interoperability and scalability while utilizing AI-driven data for predictive maintenance and dynamic spectrum management.

The practical application involves implementing ML models for forecasting resource allocation in intelligent manufacturing facilities. AI algorithms evaluate data from numerous interconnected sensors and equipment to forecast peak consumption periods in this situation. This enables the network to assign additional spectrum to certain slices that necessitate increased bandwidth. Another use involves autonomous vehicle communication. AI optimizes the spectrum for Vehicle-to-Everything (V2X) communication, guaranteeing ultra-reliable low-latency connection with latency as minimal as 0.1 milliseconds to prevent accidents. Mobile edge computers will enhance performance by positioning computer resources nearer to the edge, thereby diminishing latency and facilitating real-time execution of essential operations such as drone management and remote surgery. Through the integration of AI, ML, and MEC, 6G networks will facilitate the efficient allocation of resources across diverse slices, addressing the individual QoS requirements of distinct applications while optimizing spectral efficiency and minimizing energy usage throughout the network.

H. Terrestrial-Based and Non-Terrestrial-Based Networks

The combined deployment of 6G terrestrial and Non-Terrestrial Networks (NTNs) would augment global connectivity by facilitating immersive communication, air mobility, and dynamic resource allocation. [97, 98]. Low Earth orbit (LEO) satellites, AI-driven beamforming, and adaptable resource management will enable NTNs to overcome the constraints of terrestrial networks, facilitating essential applications such as eMBB and mMTC [99]. Technologies like nomadic non-public networks and adaptive path selection will enhance the efficiency of NTNs [100]. At the same time, developments in RATs and key performance indicators facilitate the development of global, robust, and reliable 6G systems [101]. The sixth generation (6G) wireless networks will markedly improve both terrestrial and non-terrestrial networks, presenting new opportunities and problems for wireless spectrum utilization. Terrestrial networks, such as conventional cell towers, small cells, and Wi-Fi, will gain from developments in spectrum utilization, artificial intelligence, and machine learning, hence optimizing resource allocation and enhancing user experiences. These networks will utilize massive MIMO, beamforming techniques, and complex modulation algorithms to enhance spectrum utilization and facilitate high data rate, crucial for applications such as high-definition video streaming, smart city infrastructure, and industrial automation. Nonetheless, obstacles such as interference control, the necessity for dense deployment in urban environments, and energy consumption will necessitate creative solutions, including AI-driven network management and advanced energy harvesting techniques. Conversely, non-terrestrial networks, such as satellite communications and High-Altitude Platforms (HAPs), will broaden the coverage of 6G networks into underserved and isolated regions, delivering connections where terrestrial networks are constrained or nonexistent. These networks can utilize Low Earth Orbit (LEO) satellites for instantaneous data transmission and Integrated Sensing and Communication (ISAC) to merge communication with environmental monitoring. Practical applications encompass disaster response situations where connectivity is essential, however difficult due to infrastructural destruction. Nonetheless, issues such as heightened latency in satellite communication, spectrum congestion, and the integration of non-terrestrial components with terrestrial networks must be resolved. The effective integration of terrestrial and non-terrestrial networks necessitates stringent standards for spectrum management, coordination, and seamless transitions between various network types to guarantee a cohesive and efficient communication experience. Leveraging the advantages of both terrestrial and non-terrestrial networks, 6G can establish a global, resilient, and highly adaptive communication infrastructure, facilitating innovative applications such as global IoT connectivity, smart agriculture, and comprehensive emergency response systems while concurrently tackling the technical and operational challenges associated with this integration.

I. Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surface (RIS) represents a groundbreaking technology that, through its unique characteristics and capabilities, can accelerate the achievement of ubiquitous connectivity [102, 103]. Implementing RIS in 6G networks presents various technical challenges and security concerns, especially regarding spectrum sensing and resource management. The deployment complexity presents a significant challenge, requiring the configuration of thousands of small antennas to achieve optimal signal reflection and transmission, particularly in urban settings. Obtaining precise Channel State Information (CSI) is essential for the effective operation of RIS, requiring sophisticated methods like deep learning algorithms for real-time channel estimation and compressed sensing techniques to reconstruct signals with minimal data efficiently. Adaptive beamforming is utilized to flexibly modify antenna patterns, enhancing signal quality and reducing interference in environments with multiple users. In contrast, efficient algorithms for detecting multiple users handle concurrent connections by isolating and amplifying the signals of each user. Moreover, implementing Orthogonal Frequency-Division Multiplexing (OFDM) is crucial in managing interference. In security, implementing advanced measures like Quantum Key Distribution (QKD) is essential for protecting communications from eavesdropping, as they guarantee that any attempts at interception can be detected. Secure Multi-Party Computation (SMPC) facilitates privacy-preserving data sharing among multiple users, an essential component for RIS collaborative applications. Utilizing blockchain for access control guarantees that only permitted devices can connect to RIS-enabled networks while also maintaining an unalterable record of access attempts. Furthermore, strong anomaly detection algorithms utilizing machine learning can improve spectrum sensing by recognizing and addressing spoofing attempts. Additionally, integrating cross-layer security mechanisms that combine physical-layer security with network-layer protocols can strengthen the resilience of the network. The technical aspects collectively underscore the complex interplay between leveraging RIS technology for improved performance and maintaining strong security measures in 6G networks. Free-space optics is viable for delivering broadband internet connectivity to High-Speed Trains (HSTs). Moreover, RIS is regarded as hardware technology that enhances the performance of optical wireless communication systems [104]. Utilizing a single RIS (S-RIS) may constrain specific application situations and be inadequate for guaranteeing reliable communication between transmitters and receivers [105].

J. Efficient Regulatory Frameworks

Multiple technical techniques must be employed to establish resilient regulatory frameworks for equal access and effective spectrum management in 6G networks. Dynamic Spectrum Access (DSA) protocols permit users to access spectrum bands according to real-time availability and demand, enhancing resource usage using methods such as cognitive radio, which dynamically detects and adjusts to the spectrum environment. Advanced spectrum sensing technologies, including machine learning algorithms and distributed sensing networks, can precisely identify unused spectrum bands, improving the recognition of primary users and mitigating interference in shared access scenarios. Regulatory standards for spectrum sharing must be established, encouraging models such as Licensed Shared Access (LSA) and unlicensed access, which delineate user rights and obligations while fostering collaboration between commercial operators and public institutions. Establishing established interoperability standards, such as IEEE 802.22 for wireless regional area networks, facilitates seamless communication among diverse devices and networks, improving overall efficiency. Regulatory frameworks may encompass technical requirements for incentive-based spectrum leasing models designed to promote investment in rural and underserved regions by providing reduced rates for spectrum access. Utilizing modern algorithms for spectrum allocation, including genetic algorithms and artificial intelligence techniques, can enhance resource distribution according to real-time demand and consumption trends. Furthermore, implementing a compliance monitoring system utilizing blockchain technology improves transparency in spectrum utilization by recording all transactions, ensuring accountability, and facilitating regulatory enforcement. Ultimately, providing resources for research and development in developing spectrum management technologies, such as network slicing and multi-access edge computing, can foster innovation and enhance the overall efficiency of 6G networks. Alongside pivotal protocols like IEEE 802.11 (Wi-Fi) and IEEE 802.22 (cognitive radio for WRAN), numerous additional standards are critical for spectrum management and communication in 6G networks. IEEE 802.15.4 delineates Low-Rate Wireless Personal Area Networks (LR-WPANs), frequently utilized in IoT applications, whilst IEEE 802.1X offers port-based network access control, augmenting security in wireless networks. The ITU-R recommendations govern radio frequency management and spectrum allocation, including specific standards such as ITU-R M.2101 for mobile communications. The NR standard, a component of 3GPP standards, delineates radio access technology for 5G and subsequent generations, emphasizing enhanced performance and efficiency. The management of the 6G spectrum can enhance energy efficiency using several methods and technologies. Principal protocols encompass IEEE 802.15.4 for low-energy IoT communications, NR from 3GPP for enhanced resource allocation, and IEEE 802.11ax (Wi-Fi 6) for effective data transmission. Methods like massive MIMO, beamforming, and DSA improve spectral efficiency and decrease energy usage. Furthermore, the use of Multi-Access Edge Computing (MEC) facilitates localized processing, hence reducing energy expenditures associated with data transmission by positioning computation nearer to the user. Additional pertinent protocols comprise ETSI EN 303 345 (pertaining to low-power wide-area networks), IEEE 802.1AE (MAC security for protecting data transmissions), and ITU-T recommendation G.9991 (focused on energy-efficient home networking). SCTE 2050 standardizes the provision of broadband services across diverse technologies, pertinent for the integration of many access ways. The ETSI GS MEC 003 emphasizes Multi-access edge computing (MEC), facilitating low-latency services through data processing near end-users. Networking protocols like IETF RFC 793 (transmission control protocol) and IETF RFC 2460 (internet protocol version 6) are essential for dependable data transmission and extensive addressing capabilities, respectively. Finally, Wi-Fi HaLow (IEEE 802.11ah) presents a low-power, long-range Wi-Fi standard intended for IoT devices functioning in sub-1 GHz frequencies. These protocols together augment the possibilities and efficiency of communication inside the advancing realm of 6G networks.

K. Intelligent Reflecting Surfaces (IRS)

Intelligent Reflecting Surfaces (IRS) have the potential to significantly enhance wireless communication by adeptly managing signal transmission. Essential technical standards, including 3GPP releases 16 and 17, delineate the incorporation of Intelligent Reflecting Surfaces (IRS) into 5G and forthcoming 6G networks, emphasizing performance metrics and system design. Moreover, standards like as ITU-T Y.3100 for 6G architecture and IEEE 802.15 for low-power wireless networks delineate frameworks for IRS applications. The IEEE 802.11ax (Wi-Fi 6) specifications facilitate the implementation of IRS in Wi-Fi networks, improving signal quality and coverage. The IRS will employ sophisticated routing protocols like as Optimized Link State Routing (OLSR) and Ad hoc On-Demand Distance Vector (AODV) to facilitate effective path selection predicated on enhanced signal quality. Beamforming techniques, such as Maximum Ratio Transmission (MRT) and Zero-Forcing Beamforming (ZFBF), will enhance signal transmission by guiding beams toward users and reducing interference. Moreover, channel estimation algorithms like Least Squares Estimation (LSE) and Minimum Mean Square Error (MMSE) would improve the accuracy of channel state information for optimal IRS reflection. The comprehensive network architecture will consist of Base Stations (BS) collaborating with IRS for signal management, User Equipment (UE) experiencing enhanced connectivity, and a controller supervising IRS functions and real-time resource distribution, thereby facilitating effective communication in progressively intricate 6G settings. Consequently, the IRS will promote a more flexible and effective utilization of the wireless spectrum, tackling the difficulties associated with high-density environments and varied application demands. and improved user experiences, facilitating the development of sophisticated applications such as augmented reality and the Internet of Things (IoT). This breakthrough technology is anticipated to revolutionize the operation of wireless networks, enhancing their intelligence and responsiveness to user and application requirements.

V. 6G APPLICATIONS

6G applications are on the edge of transforming various industries with unparalleled capabilities. 6G is expected to not only improve mobile broadband speeds and latency, but also enable advanced technologies like holographic communications, ubiquitous Augmented Reality (AR), and Virtual Reality (VR) environments which combine physical and digital realities. Fig. 12 describes the detailed application of 6G sectors, such as healthcare, which could experience advantages from real-time remote surgeries enabled by Ultra-Reliable Low-Latency Communications (URLLC), while smart cities could enhance energy efficiency and traffic management by seamlessly connecting IoT devices.

Furthermore, the ability of 6G to provide autonomous cars with immediate data processing and decision-making abilities has the potential to revolutionize transportation safety and efficiency. As these applications progress, 6G is ready to enable a new era of innovation driven by connectivity in global economies and society.

A. Social and Economic Benefits

The introduction of the next-generation spectrum opens up possibilities for start-ups, entrepreneurs, and technology firms to establish novel applications, offerings, services, and business models for experimental reasons, such as regulatory sandboxes, which promote experimentation and the creation of cutting-edge technologies and services because 6G standards are dominating rapidly [79, 80]. This encourages the development of the digital economy, creates jobs, and enhances economic competitiveness, all of which will lead to economic growth. The digital gap will be bridged, and the connection to socioeconomic growth will be improved through the following generation spectrum. These developments spur digital change across sectors, boost productivity, and open fresh commercial prospects. The new radio spectrum's accessibility encourages business and innovation. Effective disaster management, public security, and crisis response are made possible by dedicated spectrum bands for public safety services. These bands also allow dependable and robust communication networks for emergency responders. When communication is better, lives are saved, and communities are safeguarded.

B. Environmental Impact

The introduction of new radio frequencies and cutting-edge technology may have an impact on the environment. Utilizing the spectrum more effectively lowers energy use and promotes sustainability. Precision agriculture, environmental monitoring, intelligent energy management, and other applications that support environmentally friendly development and lessen ecological impact can all be made possible by wireless communication technologies. Advanced spectrum sharing can enhance both spectral efficiency and energy efficiency in a cost-effective manner, which is expected to perform much better than conventional networks.

C. Limitations of Curren Paper

The frameworks and concepts presented in this paper are considered to be in preliminary developmental stages or suggested for future advancement, requiring additional research and development. To improve the thoroughness of this work, it is essential to examine the present constraints and limitations of every topic, unresolved challenges, and appropriate preliminary research before the proposed research or framework. This study analyzes the existing literature on 6G applications, opportunities, and challenges, establishing a foundation for understanding the current state of the field. The scope is being expanded to encompass critical areas, including 6G spectrum opportunities, industrial challenges, and the necessary architectural frameworks for effective spectrum management. The most important topics examined include dynamic spectrum access, unlicensed spectrum utilization, resource allocation strategies, network slicing, and the incorporation of emerging technologies like Artificial Intelligence (AI). Furthermore, advanced methodologies such as Intelligent Reflecting Surfaces (IRS), Reconfigurable Intelligent Surfaces (RIS), and the interaction between terrestrial and non-terrestrial networks have been investigated to emphasize their potential to respond to recent developments. The discussion associated with 6G applications highlights the potential transformative effects of these technologies on various industries and society broadly. An exploration of existing gaps and challenges, in conjunction with relevant foundational work, provides critical context and delineate a pathway for future research in the advancement of 6G development.

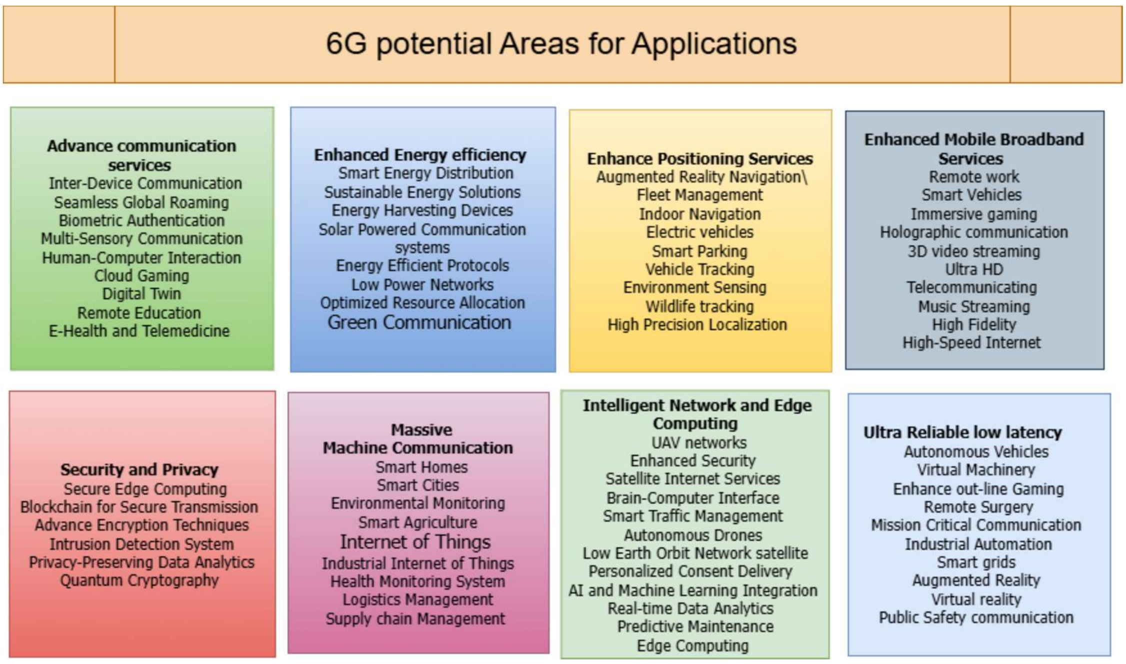

Fig. 12. 6G potential areas for applications.

VI. CONCLUSION

This paper investigates the notable progress in 6G wireless spectrum technologies, emphasizing their capacity to provide ultra-high data speeds, extensive connectivity, and minimal latency through AI integration and advanced protocols. It rigorously examines resource distribution, highlighting the need for inventive approaches to properly tackle these concerns. The insights acquired will drive future research trajectories and development initiatives, ultimately advancing efficient and secure 6G networks. Guarantee that these technologies can coexist and function collaboratively to realize the complete potential of the IoT. Spectrum education is essential to actualize the comprehensive vision and advantages for future generations within society and to promote the advancement of innovative spectrum techniques and services; the foremost issues in this decade include spectrum design, characterization standardization, policy, management, and regulations for future generations. 6G is now in the development phase some of the phases suggested. The first stage was to specify what should be measured at gigahertz and terahertz frequencies and which bands should be used for each. the second stage included outlining the deployment's architectural framework and the third involved detailing all the technical requirements for deploying the next-gen spectrum. Now. 6G and beyond have reached the testing phase. Despite this, there are still issues that need to be resolved for mobile network operator's product developers, and vendors, such as industry forums or industrial deployment regulation bodies, standards for organizations, technical standards, product certification regulations on a national and international level, spectrum (regulations for national and global level, spectrum licenses, etc.) policies market, price, and so on. Spectrum reallocation experiments have been started in several countries, and the findings are now being analyzed. Various places throughout the world have developed plans for the introduction of a new radio spectrum. It is critical in the present period for deployment scenarios for future generations to characterize, share, analyze, and deploy spectrum in the frequency range. A wide variety of frequencies are available in the 6G spectrum, Spectrum management and regulations are critical to the success of national and international mobile carriers, as well as the success of product vendors, via dynamic policy. The future generation spectrum for IoT will be characterized by different wireless technologies optimized for other use cases and environments. The critical challenge will be to ensure that these technologies can coexist and operate together seamlessly to enable the full potential of the IoT. Spectrum education is necessary to realize the full vision and benefits of future generations for society and to encourage the development of novel spectrum techniques and services; the most pressing concerns in this decade are spectrum design, characterization standardization, policy, management, and regulations for the future generation.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest regarding this manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization, Farhan Ali, He Yigang; methodology, Farhan Ali, He Yignag, Cheng Wei Ding; software, Farhan Ali, Atta Rahman, Mohammad Ahmad Saleem Khasawneh; formal analysis, Farhan Ali; investigation, Farhan Ali, He Yigang; resources, He Yigang; data curation, Farhan Ali, Cheng Wei Ding, Atta-ur Rahman; writing—original draft preparation, Farhan Ali; writing—review and editing, Farhan Ali, He Yigang, Cheng Wei Ding, Atta-ur Rahman, Mohammad Ahmad Saleem Khasawneh; visualization, Farhan Ali; supervision, He Yigang; project administration, He Yigang; all authors had approved the final version.

FUNDING

This work was supported by the National Natural Science Foundation of China under Grant No. 51977153, 51977161, 51577046, the State Key Program of the National Natural Science Foundation of China under Grant No. 51637004, the national key research and Development plan "important scientific instruments and Equipment development" Grant No.2016YFF0102200, Equipment research project in advance Grant No.41402040301.

REFERENCES

[1] I. F. Akyildiz, A. Kak, and S. Nie, "6G and beyond: The future of wireless communications systems," *IEEE Access*, vol. 8, pp. 133995–134030, 2020. doi: 10.1109/ACCESS.2020.3010896

[2] W. Saad, M. Bennis, and M. Chen, "A vision of 6G wireless systems: Applications, trends, technologies, and open research problems," *IEEE Netw*. vol. 34, no. 3, pp. 134–142, 2020. doi: 10.1109/MNET.001.1900287

[3] C. D. Alwis *et al.*, "Survey on 6G frontiers: Trends, applications, requirements, technologies and future research," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 836–886, 2021. doi: 10.1109/OJCOMS.2021.3071496

[4] Y. Wu, *et al., 6G Mobile Wireless Networks*, Berlin, Germany: Springer, 2021.

[5] H. Ahmadi, A. Nag, Z. Khar, K. Sayrafian, and S. Rahardja, "Networked twins and twins of networks: An overview on the relationship between digital twins and 6G," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 154–160, 2021. doi: 10.1109/MCOMSTD.0001.2000041

[6] M. Z. Chowdhury, M. Shahjalal, S. Ahmed, and Y. M. Jang, "6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions," *IEEE Open Journal of the Communications Society*, vol. 1, pp. 957–975, 2020. doi: 10.1109/OJCOMS.2020.3010270.

[7] B. Zong, C. Fan, X. Wang, X. Duan, B. Wang, and J. Wang, "6G technologies: Key drivers, core requirements, system architectures, and enabling technologies," *IEEE Vehicular Technology Magazine*, vol. 14, no. 3, pp. 18–27, 2019. doi: 10.1109/MVT.2019.2921398

[8] H. Kaushik, "Shifting towards 6G from 5G wireless networks—Advancements, opportunities and challenges," *Journal of Electronics, Computer Networking and Applied Mathematics (JECNAM)*, vol. 2, no. 06, pp. 20–29, Nov. 2022. doi: 10.55529/jecnam.26.20.29

[9] M. Banafaa *et al.*, "6G mobile communication technology: Requirements, targets, applications, challenges, advantages, and opportunities," *Alexandria Engineering Journal*, vol. 64, pp. 245–274, 2023. doi: https://doi.org/10.1016/j.aej.2022.08.017

[10] S. A. Abdel Hakeem, H. H. Hussein, and H. Kim, "Security requirements and challenges of 6G technologies and applications," *Sensors*, vol. 22, no. 5, 2022. doi: 10.3390/s22051969

[11] P. Kohli, S. Sharma, and P. Matta, "Secured authentication schemes of 6G driven vehicular communication network in industry 5.0 Internet-of-Everything (IoE) applications: challenges and opportunities," in *2022 IEEE 2nd International Conference on Mobile Networks and Wireless Communications (ICMNWC)*, 2022, pp. 1–5. doi: 10.1109/ICMNWC56175.2022.10031781

[12] M. M. Qureshi, M. T. Riaz, S. Waseem, M. A. Khan, and S. Riaz, "The advancements in 6G technology based on its applications, research challenges and problems: A review," in *Proc. 27th International Conference on Evaluation and Assessment in Software Engineering*, New York, NY, USA: Association for Computing Machinery, 2023, pp. 480–486. doi: 10.1145/3593434.3593965

[13] A. Almomani and F. Al-Turjman, "Challenges and opportunities in integrated 6G and IoT paradigms: An overview," in *Proc. 2022*

International Conference on Artificial Intelligence in Everything (AIE), 2022, pp. 140–145. doi: 10.1109/AIE57029.2022.00033

[14] H. Zhang, N. Shlezinger, F. Guidi, D. Dardari, and Y. C. Eldar, "6G wireless communications: From far-field beam steering to near-field beam focusing," *IEEE Communications Magazine*, vol. 61, no. 4, pp. 72–77, 2023. doi: 10.1109/MCOM.001.2200259

[15] R. Singh, G. Srivastav, R. Kashyap, and S. Vats, "Study on zero-trust architecture, application areas & challenges of 6g technology in future," in *Proc. 2023 International Conference on Disruptive Technologies (ICDT)*, 2023, pp. 375–380. doi: 10.1109/ICDT57929.2023.10150745

[16] H.-B. Jeon *et al.*, "Free-space optical communications for 6G wireless networks: Challenges, opportunities, and prototype validation," *IEEE Communications Magazine*, vol. 61, no. 4, pp. 116–121, Apr. 2023. doi: 10.1109/MCOM.001.2200220

[17] B. Gera, Y. S. Raghuvanshi, O. Rawlley, S. Gupta, A. Dua, and P. Sharma, "Leveraging AI-enabled 6G-driven IoT for sustainable smart cities," *International Journal of Communication Systems*, vol. 36, no. 16, Nov. 2023. doi: 10.1002/dac.5588

[18] P. R. Singh, V. K. Singh, R. Yadav, and S. N. Chaurasia, "6G networks for artificial intelligence-enabled smart cities applications: A scoping review," *Telematics and Informatics Reports*, vol. 9, p. 100044, Mar. 2023. doi: 10.1016/j.teler.2023.100044

[19] A. Rajagopal, S. Ahmad, S. Jha, H. A. M. Abdeljaber, and J. Nazeer, "AI based secure analytics of clinical data in cloud environment: Towards smart cities and healthcare," *Journal of Advances in Information Technology*, vol. 14, no. 5, pp. 1132–1142, 2023. doi: 10.12720/jait.14.5.1132-1142

[20] Z. Qadir, K. N. Le, N. Saeed, and H. S. Munawar, "Towards 6G Internet of Things: Recent advances, use cases, and open challenges," *ICT Express*, vol. 9, no. 3, pp. 296–312, Jun. 2023. doi: 10.1016/j.icte.2022.06.006

[21] M. Sun and L. Sun, "Harnessing the power of 6G connectivity for advanced big data analytics with deep learning," *Wirel. Pers. Commun.*, May 2024. doi: 10.1007/s11277-024-11044-z

[22] Z. Lv, R. Lou, J. Li, A. K. Singh, and H. Song, "Big data analytics for 6G-enabled massive Internet of Things," *IEEE Internet Things J.*, vol. 8, no. 7, pp. 5350–5359, Apr. 2021. doi: 10.1109/JIOT.2021.3056128

[23] G. Lax and A. Russo, "Blockchain-based access control supporting anonymity and accountability," *Journal of Advances in Information Technology*, vol. 11, no. 4, pp. 186–191, 2020. doi: 10.12720/jait.11.4.186-191

[24] V. Stepanova and I. Eriņš, "The blockchain-based model for professional growth data processing," *Journal of Advances in Information Technology*, vol. 12, no. 4, 2021. doi: 10.12720/jait.12.4.319-326

[25] Y. Cao, Y. Li, Q. Sun, Y. Sun, G. Luo, and B. Liu, "Cloud and network operating system for 6G: Definition, architecture and challenges," in *2022 IEEE Globecom Workshops (GC Wkshps)*, Dec. 2022, pp. 1212–1217. doi: 10.1109/GCWkshps56602.2022.10008688

[26] G. Senthilkumar, K. Tamilarasi, N. Velmurugan, and J. K. Periasamy, "Resource allocation in cloud computing," *Journal of Advances in Information Technology*, vol. 14, no. 5, pp. 1063–1072, 2023. doi: 10.12720/jait.14.5.1063-1072

[27] L. Kong *et al.*, "A survey for possible technologies of micro/nanomachines used for molecular communication within 6G application scenarios," *IEEE Internet Things J.*, vol. 10, no. 13, pp. 11240–11263, 2023. doi: 10.1109/JIOT.2023.3255412

[28] L. Ismail and R. Buyya, "Artificial intelligence applications and self-learning 6G networks for smart cities digital ecosystems: Taxonomy, challenges, and future directions," *Sensors*, vol. 22, no. 15, 2022. doi: 10.3390/s22155750

[29] C. C. González, S. Pizzi, M. Murroni, and G. Araniti, "Multicasting over 6G non-terrestrial networks: A softwarization-based approach," *IEEE Vehicular Technology Magazine*, vol. 18, no. 1, pp. 91–99, 2023. doi: 10.1109/MVT.2022.3232919

[30] T. S. Rappaport *et al.*, "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," *IEEE Access*, vol. 7, pp. 78729–78757, 2019. doi: 10.1109/ACCESS.2019.2921522

[31] H. Lee *et al.*, "Towards 6G hyper-connectivity: Vision, challenges, and key enabling technologies," *Journal of Communications and Networks*, vol. 25, no. 3, pp. 344–354, Jun. 2023. doi: 10.23919/JCN.2023.000006

[32] M. Chafii, L. Bariah, S. Muhaidat, and M. Debbah, "Twelve scientific challenges for 6G: Rethinking the foundations of communications theory," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 2, pp. 868–904, 2023. doi: 10.1109/COMST.2023.3243918

[33] F. Ali, H. Yigang, and R. Yi, "A novel security architecture of Internet of Things," *International Journal of Computer Theory and Engineering*, vol. 11, no. 5, pp. 89–96, 2019. doi: 10.7763/IJCTE.2019.V11.1249

[34] Q. Liu, S. Sarfraz, and S. Wang, "An overview of key technologies and challenges of 6G," in *Machine Learning for Cyber Security*, X. Chen, H. Yan, Q. Yan, and X. Zhang, Eds., Cham: Springer International Publishing, 2020, pp. 315–326.

[35] X. You *et al.*, "Toward 6G TKμ extreme connectivity: Architecture, key technologies and experiments," *IEEE Wirel. Commun.*, vol. 30, no. 3, pp. 86–95, 2023. doi: 10.1109/MWC.004.2200482

[36] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, "6G wireless systems: Vision, requirements, challenges, insights, and opportunities," *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166–1199, 2021. doi: 10.1109/JPROC.2021.3061701

[37] X. You *et al.*, "Towards 6G wireless communication networks: Vision, enabling technologies, and new paradigm shifts," *Science China Information Sciences*, vol. 64, no. 1, p. 110301, 2020. doi: 10.1007/s11432-020-2955-6

[38] H. H. Mahmoud, A. A. Amer, and T. Ismail, "6G: A comprehensive survey on technologies, applications, challenges, and research problems," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 4, p. e4233, Apr. 2021. doi: https://doi.org/10.1002/ett.4233

[39] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wirel. Commun.*, vol. 27, no. 2, pp. 218–228, 2020. doi: 10.1109/MWC.001.1900333

[40] S. Iyer, "Machine learning enabled dynamic spectrum access for 6G wireless networks," *Journal of Applied Security Research*, vol. 19, no. 2, pp. 330–350, Apr. 2024. doi: 10.1080/19361610.2023.2226014

[41] T. A. Kuzovkova, V. O. Tikhvinskiy, O. I. Sharavova, and E. E. Devyatkin, "Examining the impact of strategic trends on radio frequency spectrum requirements in mobile communication system," in *Proc. 2023 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SYNCHROINFO*, IEEE, Jun. 2023, pp. 1–5. doi: 10.1109/SYNCHROINFO57872.2023.10178666

[42] S. Markkandan, P. Santhosh Kumar, P. R, K. Vengatesan, and G. Bindu, "Spectrum management in 6G HetNet based on smart contracts and harmonized software-defined networking-enabled approach," *International Journal of Computer Networks and Applications*, vol. 10, no. 2, p. 231, Apr. 2023. doi: 10.22247/ijcna/2023/220738

[43] W. Jiang and H. D. Schotten, "Full-spectrum wireless communications for 6G and beyond: From microwave, millimeter-wave, terahertz to lightwave," in *Proc. 2023 IEEE 3rd International Conference on Computer Communication and Artificial Intelligence (CCAI)*, IEEE, May 2023. pp. 353–357. doi: 10.1109/CCAI57533.2023.10201316

[44] Y. Liu, H. Zhou, Y. Deng, and A. Nallanathan, "Channel access optimization in unlicensed spectrum for downlink URLLC: Centralized and federated DRL approaches," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 7, pp. 2208–2222, Jul. 2023. doi: 10.1109/JSAC.2023.3280982

[45] L. Zhang, Z. Wei, L. Wang, X. Yuan, H. Wu, and W. Xu, "Spectrum sharing in the sky and space: A survey," *Sensors*, vol. 23, no. 1, p. 342, Dec. 2022. doi: 10.3390/s23010342

[46] S. Iyer, "Machine learning enabled dynamic spectrum access for 6G wireless networks," *Journal of Applied Security Research*, vol. 19, no. 2, pp. 330–350, Apr. 2024. doi: 10.1080/19361610.2023.2226014

[47] T. A. Kuzovkova, V. O. Tikhvinskiy, O. I. Sharavova, and E. E. Devyatkin, "Examining the impact of strategic trends on radio frequency spectrum requirements in mobile communication system," in *Proc. 2023 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SYNCHROINFO)*, IEEE, Jun. 2023, pp. 1–5. doi: 10.1109/SYNCHROINFO57872.2023.10178666

[48] A. Medeisis and P. Faris, "Monte Carlo modelling of mmWave 6G systems for shared spectrum deployments," in *Proc. 2023 17th European Conference on Antennas and Propagation (EuCAP)*, IEEE, Mar. 2023, pp. 1–5. doi: 10.23919/EuCAP57121.2023.10132999

[49] J. Liu, X. Hou, W. Liu, L. Chen, Y. Kishiyama, and T. Asai, "Unified 6G waveform design based on DFT-s-OFDM enhancements," *IEICE Transactions on Communications*, vol. 106, no. 6, pp. 528–537, Jun. 2023. doi: 10.1587/transcom.2022EBP3123

[50] Q. Wu, W. Wang, Z. Li, B. Zhou, Y. Huang, and X. Wang, "SpectrumChain: A disruptive dynamic spectrum-sharing framework for 6G," *Science China Information Sciences*, vol. 66, no. 3, p. 130302, Mar. 2023. doi: 10.1007/s11432-022-3692-5

[51] P. Jain, A. Gupta, N. Kumar, and M. Guizani, "Dynamic and efficient spectrum utilization for 6G with THz, mmWave, and RF band," *IEEE Trans. Veh. Technol.*, vol. 72, no. 3, pp. 3264–3273, Mar. 2023. doi: 10.1109/TVT.2022.3215487

[52] O. Z. Aletri, T. E. H. El-Gorashi, and J. M. H. Elmirghani, *Resource Allocation in 6G Optical Wireless Systems*, Cham: Springer International Publishing, 2021, pp. 187–206. doi: 10.1007/978-3-030-72777-2_10

[53] W. K. Alsaedi, H. Ahmadi, Z. Khan, and D. Grace, "Spectrum options and allocations for 6G: A regulatory and standardization review," *IEEE Open Journal of the Communications Society*, vol. 4, pp. 1787–1812, 2023. doi: 10.1109/OJCOMS.2023.3301630

[54] M. Alnakhli, "Optimizing spectrum efficiency in 6G multi-UAV networks through source correlation exploitation," *EURASIP J. Wirel. Commun. Netw.*, vol. 2024, no. 1, p. 6, Jan. 2024. doi: 10.1186/s13638-023-02332-6

[55] S. Alraih *et al.*, "Revolution or evolution? Technical requirements and considerations towards 6G mobile communications," *Sensors*, vol. 22, no. 3, p. 762, Jan. 2022. doi: 10.3390/s22030762

[56] J. Rodriguez *et al.*, "Secure virtual mobile small cells: A stepping stone toward 6G," *IEEE Communications Standards Magazine*, vol. 5, no. 2, pp. 28–36, Jun. 2021. doi: 10.1109/MCOMSTD.001.2000019

[57] R. K. Saha, "Underlay cognitive radio millimeter-wave spectrum access for in-building dense small cells in multi-operator environments toward 6G," in *Proc. 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC)*, IEEE, Oct. 2020, pp. 1–6. doi: 10.1109/WPMC50192.2020.9309471

[58] R. K. Saha, "Power-domain based dynamic millimeter-wave spectrum access techniques for in-building small cells in multioperator cognitive radio networks toward 6G," *Wirel. Commun. Mob. Comput.*, vol. 2021, pp. 1–13, May 2021. doi: 10.1155/2021/6628751

[59] K.-L. Wong, Y.-R. Chen, and W.-Y. Li, "Eight-Planar-Monopole MIMO circular array generating eight uncorrelated waves for 6G upper mid-band 8 × 8 MIMO access points," *IEEE Access*, vol. 11, pp. 68018–68030, 2023. doi: 10.1109/ACCESS.2023.3292345

[60] K.-L. Wong, C.-J. Ho, and W.-Y. Li, "Low-Profile Six-Port circular patch antenna with six triple-shorted dual-resonant 60°-disk sectors to generate six uncorrelated waves for wideband mobile MIMO antennas," *IEEE Access*, vol. 10, pp. 80277–80288, 2022. doi: 10.1109/ACCESS.2022.3195541

[61] Y. Dursun, M. B. Goktas, and Z. Ding, "Green NOMA based MU-MIMO transmission for MEC in 6G networks," *Computer Networks*, vol. 228, p. 109749, Jun. 2023. doi: 10.1016/j.comnet.2023.109749

[62] M. Cui, Z. Wu, Y. Lu, X. Wei, and L. Dai, "Near-field MIMO communications for 6G: Fundamentals, challenges, potentials, and future directions," *IEEE Communications Magazine*, vol. 61, no. 1, pp. 40–46, Jan. 2023. doi: 10.1109/MCOM.004.2200136

[63] A. A. Ajani, V. K. Oduol, Z. K. Adeyemo, and E. C. Awasume, "Comparative analysis of V-band and E-band mmWaves for green backhaul solutions for 5G ultra-dense networks," *International Journal of Electrical and Electronic Engineering & Telecommunications*, pp. 115–124, 2021. doi: 10.18178/ijeetc.10.2.115-124

[64] A. M. Ahmed, S. A. Majeed, and Y. S. Dawood, "A survey of 6G mobile systems, enabling technologies, and challenges," *International Journal of Electrical and Electronic Engineering & Telecommunications.*, pp. 1–21, 2023. doi: 10.18178/ijeetc.12.1.1-21

[65] U. R. M A and P. C R, "DRLNet: A deep reinforcement learning network for hybrid features extraction and spectrum sensing in cognitive radio networks," *Journal of Advances in Information Technology*, vol. 14, no. 6, pp. 1321–1330, 2023. doi: 10.12720/jait.14.6.1321-1330

[66] F. Ali and H. Yigang, "Spectrum sensing-focused cognitive radio network for 5G revolution," *Front Environ Sci*, vol. 11, Apr. 2023. doi: 10.3389/fenvs.2023.1113832

[67] F. Ali and H. Yigang, "Spectrum for next generation technologies," *Proceedings of the 2019 8th International Conference on Software and Information Engineering*, 2019, pp. 188–191.

[68] F. Ali, Y. He, G. Shi, Y. Sui, and H. Yuang, "Future generation spectrum standardization for 5G and Internet of Things.," *J. Commun.*, vol. 15, no. 3, pp. 276–282, 2020.

[69] P. Bhattacharya, F. Patel, V. Ralegankar, B. Thakkar, S. Tanwar, and M. Abouhawwash, *Trusted 6G-envisioned Dynamic Spectrum Allocation: A Reference Model, Layered Architecture, and Use-Case*, Singapore: Springer Nature Singapore, 2022, pp. 405–418. doi: 10.1007/978-981-19-0284-0_30

[70] W. Saad, "6G wireless systems: Challenges and opportunities," *5G and Beyond*: *Fundamentals and Standards*, pp. 201–229, 2021. doi: 10.1007/978-3-030-58197-8_7

[71] Y. Liu, H. Zhou, Y. Deng, and A. Nallanathan, "Channel access optimization in unlicensed spectrum for downlink URLLC: Centralized and federated DRL approaches," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 7, pp. 2208–2222, Jul. 2023. doi: 10.1109/JSAC.2023.3280982

[72] A. U. Khan, G. Abbas, Z. H. Abbas, M. Bilal, S. C. Shah, and H. Song, "Reliability analysis of cognitive radio networks with reserved spectrum for 6G-IoT," *IEEE Transactions on Network and Service Management*, vol. 19, no. 3, pp. 2726–2737, Sep. 2022. doi: 10.1109/TNSM.2022.3168669

[73] S. Markkandan, P. S. Kumar, P. R, K. Vengatesan, and G. Bindu, "Spectrum management in 6G HetNet based on smart contracts and harmonized software-defined networking-enabled approach," *International Journal of Computer Networks and Applications*, vol. 10, no. 2, p. 231, Apr. 2023. doi: 10.22247/ijcna/2023/220738.

[74] B. P. Tewari and S. K. Ghosh, *A Comprehensive Analysis on Bandwidth Management in 6G: Sharing, Reuse or Introducing New Bandwidth?* Singapore: Springer Nature Singapore, 2022, pp. 89–100. doi: 10.1007/978-981-19-6301-8_9

[75] C. de Alwis, Q. V. Pham, and M. Liyanage, "Security and privacy of 6G," in *6G Frontiers*, Wiley, 2022, pp. 115–149. doi: 10.1002/9781119862321.ch10

[76] V. S, R. Manoharan, S. Ramachandran, and V. Rajasekar, "Blockchain based privacy preserving framework for emerging 6G wireless communications," *IEEE Trans. Industr. Inform.*, vol. 18, no. 7, pp. 4868–4874, Jul. 2022. doi: 10.1109/TII.2021.3107556

[77] R. Bajracharya, R. Shrestha, S. A. Hassan, K. Konstantin, and H. Jung, "Dynamic pricing for intelligent transportation system in the 6G unlicensed band," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 7, pp. 9853–9868, Jul. 2022. doi: 10.1109/TITS.2021.3120015

[78] G. Naik, J.-M. Park, J. Ashdown, and W. Lehr, "Next generation Wi-Fi and 5G NR-U in the 6 GHz bands: Opportunities and challenges," *IEEE Access*, vol. 8, pp. 153027–153056, 2020. doi: 10.1109/ACCESS.2020.3016036

[79] R. Porselvi, D. Kanchana, B. Jackson, and L. Vigneash, "Dynamic resource management for 6G vehicular networks: CORA-6G offloading and allocation strategies," *The Scientific Temper*, vol. 15, no. 02, pp. 2116–2122, Jun. 2024. doi: 10.58414/SCIENTIFICTEMPER.2024.15.2.22

[80] S. F. Ismail and D. J. Kadhim, "Towards 6G technology: Insights into resource management for cloud RAN deployment," *IoT*, vol. 5, no. 2, pp. 409–448, Jun. 2024. doi: 10.3390/iot5020020

[81] R. Dangi and P. Lalwani, "Optimizing network slicing in 6G networks through a hybrid deep learning strategy," *J. Supercomput.*, vol. 80, no. 14, pp. 20400–20420, Sep. 2024. doi: 10.1007/s11227-024-06238-y

[82] N. Hui, Q. Sun, L. Tian, Y. Wang, and Y. Zhou, "Computation and wireless resource management in 6G space-integrated-ground access networks," *Digital Communications and Networks*, Apr. 2024. doi: 10.1016/j.dcan.2024.04.001

[83] R. K. Yadav, S. Chattopadhyay, P. Jaidka, and P. Upadhyay, "Performance analysis of cloud-assisted resource allocation algorithms in 6G networks," in *Proc. 2024 2nd International Conference on Disruptive Technologies (ICDT)*, IEEE, Mar. 2024, pp. 1038–1043. doi: 10.1109/ICDT61202.2024.10489750

[84] A. M. Alwakeel and A. K. Alnaim, "Network slicing in 6G: A strategic framework for IoT in smart cities," *Sensors*, vol. 24, no. 13, p. 4254, Jun. 2024. doi: 10.3390/s24134254

[85] M. Ameur, B. Brik, and A. Ksentini, "Leveraging LLMs to eXplain DRL decisions for transparent 6G network slicing," in *Proc. 2024 IEEE 10th International Conference on Network Softwarization (NetSoft)*, IEEE, Jun. 2024, pp. 204–212. doi: 10.1109/NetSoft60951.2024.10588921

[86] A. M. Escolar, J. B. Bernabe, J. M. A. Calero, Q. Wang, and A. Skarmeta, "Network slicing as 6G security mechanism to mitigate cyber-attacks: The RIGOUROUS approach," in *Proc. 2024 IEEE 10th International Conference on Network Softwarization (NetSoft)*, IEEE, Jun. 2024, pp. 387–392. doi: 10.1109/NetSoft60951.2024.10588887

[87] Q. Xia, J. Wang, C. Huang, and X. Yao, "Reliability-aware network slicing based on multi-objective optimization," in *Proc. 2024 IEEE Congress on Evolutionary Computation (CEC)*, IEEE, Jun. 2024, pp. 1–8. doi: 10.1109/CEC60901.2024.10611961

[88] C. T. Nguyen *et al.*, "Emerging technologies for 6G non-terrestrial-networks: From academia to industrial applications," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 3852–3885, 2024. doi: 10.1109/OJCOMS.2024.3418574

[89] M. Saimler *et al.*, "The role of ai enablers in overcoming impairments in 6G networks," in *Proc. 2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, IEEE, Jun. 2024, pp. 913–918. doi: 10.1109/EuCNC/6GSummit60053.2024.10597102

[90] K. B. Letaief, Y. Shi, J. Lu, and J. Lu, "Edge artificial intelligence for 6G: Vision, enabling technologies, and applications," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 1, pp. 5–36, Jan. 2022. doi: 10.1109/JSAC.2021.3126076

[91] S. A. Abdel Hakeem, H. H. Hussein, and H. Kim, "Vision and research directions of 6G technologies and applications," *Journal of King Saud University-Computer and Information Sciences*, vol. 34, no. 6, pp. 2419–2442, Jun. 2022. doi: 10.1016/j.jksuci.2022.03.019

[92] A. Alhammadi *et al.*, "Artificial intelligence in 6G wireless networks: Opportunities, applications, and challenges," *International Journal of Intelligent Systems*, vol. 2024, pp. 1–27, Mar. 2024. doi: 10.1155/2024/8845070

[93] D. Pandey, B. K. Pandey, and T. Ahmad, Eds., *Security Issues and Solutions in 6G Communications and Beyond*, IGI Global, 2024. doi: 10.4018/979-8-3693-2931-3

[94] Y. Ghildiyal *et al.*, "An imperative role of 6G communication with perspective of industry 4.0: Challenges and research directions," *Sustainable Energy Technologies and Assessments*, vol. 56, p. 103047, Mar. 2023. doi: 10.1016/j.seta.2023.103047

[95] B. Han *et al.*, "Digital twins for industry 4.0 in the 6G era," *IEEE Open Journal of Vehicular Technology*, vol. 4, pp. 820–835, 2023. doi: 10.1109/OJVT.2023.3325382

[96] M. Maier, "6G as if people mattered: From industry 4.0 toward society 5.0," in *Proc. 2021 International Conference on Computer Communications and Networks (ICCCN)*, IEEE, Jul. 2021, pp. 1–10. doi: 10.1109/ICCCN52240.2021.9522181

[97] K. Mohanta and S. Al-Rubaye, "Towards 6G satellite–terrestrial networks: Analysis of air mobility operations," *Electronics (Basel)*, vol. 13, no. 14, p. 2855, Jul. 2024. doi: 10.3390/electronics13142855

[98] Q. Huang, B. E. Youcef Belmekki, A. M. Eltawil, and M.-S. Alouini, "System-level metrics for non-terrestrial networks under stochastic geometry framework," *IEEE Communications Magazine*, vol. 62, no. 8, pp. 148–154, Aug. 2024. doi: 10.1109/MCOM.001.2300561

[99] Z. Wang, Y. Liu, R. Song, and H. Zhang, "LEO constellation design and link analysis for non-terrestrial networks," in *Proc. 2024 IEEE 6th Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, IEEE, May 2024, pp. 633–637. doi: 10.1109/IMCEC59810.2024.10575560

[100] T. Korikawa, C. Takasaki, K. Hattori, and H. Ohwada, "An adaptive rule-based path selection method using link information in non-terrestrial networks," in *Proc. 2024 IEEE 10th International Conference on Network Softwarization (NetSoft)*, IEEE, Jun. 2024, pp. 286–294. doi: 10.1109/NetSoft60951.2024.10588890

[101] H. Shahid *et al.*, "Emerging advancements in 6G NTN radio access technologies: An overview," in *2024 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, IEEE, Jun. 2024, pp. 593–598. doi: 10.1109/EuCNC/6GSummit60053.2024.10597037

[102] R. A. Roshdy and M. A. Salem, "A proposed channel estimation framework for reconfigurable-intelligent-surface-aided MIMO communication system," *IEEE Internet Things J*, vol. 10, no. 15, pp. 13612–13621, Aug. 2023. doi: 10.1109/JIOT.2023.3262674

[103] P. Ramezani, B. Lyu, and A. Jamalipour, "Toward RIS-enhanced integrated terrestrial/non-terrestrial connectivity in 6G," *IEEE Netw*, vol. 37, no. 3, pp. 178–185, May 2023. doi: 10.1109/MNET.116.2200060

[104] P. Agheli, H. Beyranvand, and M. J. Emadi, "High-speed trains access connectivity through RIS-Assisted FSO communications," *Journal of Lightwave Technology*, vol. 40, no. 21, pp. 7084–7094, Nov. 2022. doi: 10.1109/JLT.2022.3199608

[105] M. A. Salem, A. A. Hady, H. H. Hussein, and R. A. Roshdy, "Enhanced connectivity through double RIS uplink MIMO and advanced modulation," *Computers and Electrical Engineering*, vol. 119, 109486, Oct. 2024. doi: 10.1016/j.compeleceng.2024.109486