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AI-RAN in 6G Networks: State-of-the-Art and Challenges

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ABSTRACT 6G is a next-generation cellular communication technology that builds up on existing 5G networks which are currently rolled out worldwide. Through incorporation of artificial intelligence (AI) and machine learning (ML), the core 5G network is advanced into an intelligent 6G network. The 6G Artificial Intelligence Radio Access Network (AI-RAN) is anticipated to offer advanced features like reduced latency, improved bandwidth, data rates and coverage. Furthermore, AI-RAN is expected to support complex use cases such as extreme connectivity, multi-user communications and dynamic spectrum access. This paper provides a detailed survey and thorough assessment of AI-RAN's vision and state-of-the-art challenges. We first present a concise introduction to 6G AI-RAN followed by background information on the current 5G RAN and its challenges that must be overcome to implement 6G AI-RAN. The paper then examines trending research issues in AI-RAN, i.e., challenges related to spectrum allocation, network architecture, and resource management. We discuss the methods to overcome these challenges which include the adoption of advanced machine learning and edge computing technologies to boost the performance of 6G AI-RAN. We conclude by stating open research directions.

INDEX TERMS 5G, 6G, AI-RAN, AI/ML, radio and future Internet architecture.

I. INTRODUCTION

5/6G are the latest generations of cellular networks that will revolutionize how we communicate, access and use data. 5G is already a big success, with many countries rolling it out around the world such as China, the United States, Germany, Singapore etc. Based on technological and scientific evidence, 5G networks are expected to provide significantly faster speeds ranging from 100 Mbps to 10 Gbps when compared to 4G LTE networks. It is notable that the particular speed limits vary by country. Currently, the fastest recorded speed for 5G networks is around 360 Mbps [1]. The exact speed that users experience on 5G depends on several factors such as user location, the amount of available spectrum in the area, the number of other users on the network, and vice-versa. The potential applications of 5G technology includes industrial automation, virtual reality (VR) and augmented reality (AR) [2] to deliver better throughput, more reliable connections and lower latency [3] [4]. Moreover, the different use cases of 5G networks are discussed in the literature, for example in the context of the Internet of Things (IoT), which is allowing massively connected devices to communicate with each other to enable smart cities and self-driving cars [5].

6G is the next generation of mobile technology and is expected to bring even more advanced features, including speeds up to 1000 times faster than 5G, lower latency, and more efficient use of broad-spectrum [6]. It is expected that 6G will also enable new applications, such as holographic communications, extended reality (XR) based on VR/AR/MR, real-time 3D mapping, and ultra-high resolution video streaming. Further use cases include, i.e., ultra-reliable low latency communications (URLLC), ultra-reliable low latency broadband communication (ULBC), massive Ultra-reliable low latency communication (mULC), ubiquitous low latency broadband communication (uMBB), massive machine type communication (mMTC) and enhanced mobile broadband (EmBB) [7]. These applications and use cases of 6G technology will lead to improvement in the fields of e-health, smart manufacturing, e-agriculture, and smart cities. For example in health care, 6G technology embeds a new version of e-healthcare solutions, i.e., remote diagnosis, tele-medicine, remote surgery, and real-time monitoring of vital signs [8]. It will also enable new applications in smart manufacturing, i.e., autonomous robots, smart factories and e-production lines [9]. Similarly in e-agriculture, 6G will empower new services like remote sensing and precision farming [10]. Likewise, 6G also validates applications in the area of smart cities, i.e., intelligent traffic control, smart lighting and urban analytics [11].

At the heart of 6G advancing technologies, artificial intelligence (AI), machine learning (ML) and deep learning (DL) in particular are expected to play a critical role. Those roles include, for example, supporting millimeter-wave (mmWave) and terahertz (T-Hz) communications at various levels, upon the Physical layer it provides support for channel detection and modulation classification [12]. Similarly, at the link layer, DL is used for beam-forming design and channel assignment [13]. The channel in mmWave and T-Hz systems can change significantly in the micro range, resulting in a considerable rise in channel estimation frequency and associated overhead. Said challenges have been addressed by AI/ML approaches such as improved channel prediction, scheduling and optimization. The rapid growth in the deployment of 5G brings many challenges, i.e., network architecture complexity, high cost, latency issues, power consumption, and new radio systems for hybrid long-term evolution (LTE), which bring complexity in the network. In such complex scenarios, AI/ML/DL has become an important aspect that plays a central role in solving complex problems such as self-healing, self-optimization, and self-configuration in intelligent networks [14]. Many aspects will be further optimized by using DL, e.g., spectrum acquisition/sharing, slicing, radio resource management, mobility management, etc [15].

In recent years, the field of open access radio networks (ORAN) gained significant interest in the scientific and research progress regarding 5G /6G networks. Researchers have explored methodologies and technologies to enable virtualization, network slicing, and multi-vendor interoperability within ORAN frameworks, to improve the network's performance, resource allocation, and scalability. ORAN promotes open interfaces and software-defined networking to improve network flexibility, interoperability, and cost efficiency. As part of this innovation, the exploration of ORAN's use of AI has become a more important subject [16]. It will enable faster and more efficient network deployment and new use cases.

Artificial Intelligence Radio Access Networks (AI-RAN) will effectively help reduce costs and enable smarter decision-making for 6G networks. AI-RAN is an advanced version of traditional radio access networks used to connect wireless devices to the control plane and core networks [17]. For instance, AI-RAN systems can predict network traffic patterns, modify network capacity and minimize the requirement for over-provisioning. Furthermore, AI-RAN can optimize network resource allocation in real-time, ensuring that available resources are efficiently dispersed to satisfy user demands. This can assist in decreasing the costs associated with network load balancing. Furthermore, AI-RAN can assist in increasing network resilience and availability by proactively detecting and diagnosing network defects and vulnerabilities. DP approaches can scan massive volumes of network data in real-time to detect patterns and anomalies that may suggest possible problems. It can maintain 6G network availability and minimize downtime even in the face of traffic spikes. Additionally, AI-RAN can promote intelligent automation and orchestration, which can lead to smarter decision-making. AI approaches are used to automate repetitive network chores and improve network service delivery, freeing up network operators to concentrate on more strategic work. Network slicing, which enables network operators to design individualized, virtualized network partitions suited to particular user requirements, is another AI-RAN-enabled capability. While lowering costs and enabling wiser judgments, the integration of AI in RAN networks can increase network performance, dependability, and flexibility. The next generation of wireless communication networks will be able to deliver greater service quality and faster data speeds by utilizing AI. Therefore, AI and open networks have emerged as powerful technologies that enable network automation [18] and improve system performance and user experience [19]. The telecommunications industry is moving toward intelligent and open networks [20]. In addition, network measurements across AI-RAN and users can be used to make data-driven decisions about user allocation and load balancing. Therefore, mobility-aware user assignment has recently been considered as a reinforcement learning (RL) problem [21]. AI-RAN can also optimize network resource allocation in real-time, ensuring that available resources are efficiently dispersed to satisfy user demands [22]. This can assist in decreasing the costs associated with network load balancing. AI will be used in 6G to analyze user behavior [23], predict network demand [24], and optimize resource allocation [25] accordingly. Optimizing resource utilization to support economical and reliable connectivity is a key challenge in the development of 6G networks [26]. In the case of dual connectivity also known as critical connectivity [27] can integrate various communication technologies such as Wi-Fi, WiMAX, 5G, LTE, UMTS and satellite to provide a more reliable and secure communication infrastructure.

Extensive research is being conducted on different areas of 6G networks including technical needs [28], new technologies [29], DL [30], IoT [31] and Intelligent Reflecting Surfaces (IRS) [32]. There is currently a scarcity of extensive survey research on AI-RAN in the context of 6G networks.

This survey paper attempts to fill this void by giving a comprehensive review of AI-RAN advancements and problems in the transition from 5G to 6G RAN usage. This aggregated survey targets researchers and industrial experts interested in learning about the present state, possibilities, and future research directions in AI-RAN for 6G networks.

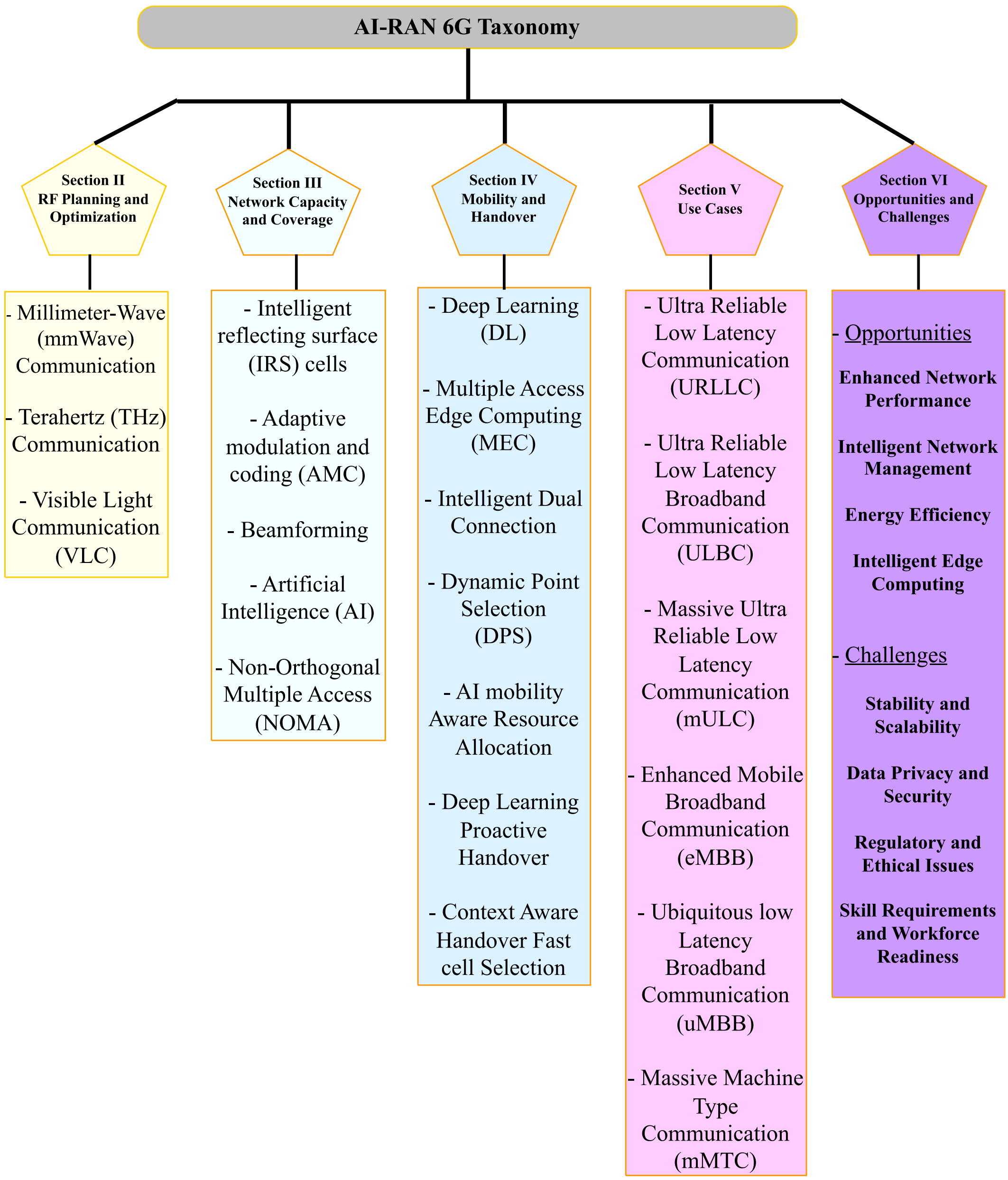

FIGURE 1. A taxonomy of key points of our survey on AI-RAN 6G.

The taxonomy is divided into six main topics to assess the existing work as illustrated in Fig. 1 RF planning and optimization are deliberated in Section II. Section III discusses network capacity and coverage. Mobility and handovers are covered in Section IV. The use cases are elaborated on in Section V. The final Section VI discusses opportunities and challenges.

II. RF PLANNING AND OPTIMIZATION IN AI-RAN 6G

Radio frequency (RF) planning and optimization are critical to effectively deploying and operating 5G/6G networks. The network designers must consider a few factors alike, to provide seamless connectivity efficient use of the spectrum, and achieve optimal QoS. Where the sub-activities include network structure, antenna characteristics, signal propagation, signal interference, and traffic requirements. Additionally, RF planning and optimization is often used as a combination of automated tools and manual operations. Automated technologies such as radio resource management (RRM) method [33], predictive analytics and machine learning approaches are used to optimize radio resource usage and improve the user experience.

The merging of mmWave and T-Hz technologies in the future network enables AI-RAN. In 5G/6G networks, RF uses mmWave and T-Hz spectrum to reach high channel capacities of gigabits per second and even terabits per second. T-Hz waves fall within the electromagnetic band between 0.3 GHz and 3 T-Hz. At the same time, mmWaves fall within the range of 30 to 300 GHz. The International Telecommunication Union (ITU) has set a frequency range of 0.275 to 0.45 T-Hz for land mobile applications and fixed line services in 2019 [34]. mmWave technology provides high data rates over long distances, and T-Hz technology provides high data rates over short distances. It uses VLC technology to provide a faster data rate over short distances and significantly improve coverage in difficult conditions. A network operator must first determine the requirements of the network and the user scenarios to be addressed. This includes specifications for network performance and coverage, as well as the target user context. The radio access network must be built and optimized according to the specifications. A successful radio access network must include RF planning and optimization. Operators can optimize their networks to meet performance and capacity requirements by using AI-RAN with mmWave, T-Hz, and VLC technologies [35].

The mmWave is a promising technique for providing gigabit connectivity in next-generation aerial networks through Monte Carlo simulation [36]. Higher frequency bands of the electromagnetic spectrum are used in mmWave technologies, which can increase data transmission rates but have shorter transmission ranges. One of mmWave technology's key advantages is its capacity to provide noticeably more excellent data rates [37], which can open up new applications and use cases including ultra-high definition (UHD) video streaming [38], virtual reality [39], and augmented reality [39]. Compared to existing methods in mmWave networks, the mm-Rrangerr can accurately perceive a given environment with low overhead, and the learned information can bring 1.6% and 2.1% performance gains in terms of network coverage and mobile link throughput, respectively [40]. In comparison to lower-frequency communications, mmWave networks can have much higher density and greater spectral efficiency, even with blocking for certain link distances [41]. In heterogeneous sub-6 GHz/mmWave cellular networks with mobility techniques can provide greater spectral efficiency and connectivity than the traditional access mode selection techniques [42]. In [43], the first cross-layer and software-defined mmWave communication system is presented in [44], It raises the possibility that mmWave communication will have an important impact on the upcoming 6G networks. However, there are several difficulties with mmWave technology, including shorter transmission ranges because of more attenuation and the requirement for more exact antenna aiming. Researchers are investigating advanced signal processing methods [45], beamforming methods [46], adaptive modulation [47] and coding strategies [48] to address these issues.

Even higher frequencies than those used in mmWave communication are used in T-Hz communication, which can permit faster data transfer rates but may encounter difficulties due to atmospheric absorption. The T-Hz communication which operates at frequencies between 0.1 and 10 T-Hz [49], is a prospective technology for 6G networks because of its capacity to provide noticeably larger bandwidth compared to existing wireless technologies. This is an efficient way to integrate broadband communications and high-resolution detection capabilities into a system in the T-Hz band, which could be useful for several future 6G applications [50]. New applications like high-resolution photography [51], ultra-high-speed data transfer [52], and low-latency communication [53] may be made possible by this enhanced bandwidth. Whereas, this is the first case of a real-time T-Hz fiber link exceeding 100 Gbps at frequencies above the 350 GHz band, paving the path for practical T-Hz and optical fiber integration in future 6G mobile communication systems [54]. Furthermore, the well-known tailed discrete

TABLE 1. RF planning and optimization key concepts.

Key Concepts	Remarks
Radio Resource Management (RRM) [33]	It is crucial for strengthening network performance and allowing seamless connectivity in RANs, especially in heterogeneous networks with multiple applications. It is predictive analytics and machine learning approaches are used to optimize radio resource usage and improve the user experience.
mmWave [37]	It allows for multi-gigabit wireless communication, outperforming in 4G and 5G networks. It focuses on user association methods, improved network performance and spectrum management.
THz [43]	Although this technology can achieve data speeds of up to 1Tbps, it is still in its early phases of development. Using T-Hz frequency technology, researchers have achieved 100 Gbps data rates.
Visible light communication (VLC) [47]	It is a viable approach for providing multi-gigabit wireless communication, with various advantages over radio frequency (RF) transmission, including increased data speeds and enhanced security. VLC, on the other hand, has constraints such as the requirement for line-of-sight communication and a limited range.
mm-Rranger [40]	To some extent, mm-Rranger signals can penetrate clouds, allowing investigation of the inner structure of clouds, including many cloud layers. This frequency range is extensively employed in high-speed wireless communication, short-range fire-control radar in tanks and aircraft, cloud observation, and atmospheric research.

Fourier transform spread orthogonal frequency division multiplexing (KT-DFT-s-OFDM) waveforms are potential candidates for deployment in 6G sub-THz frequencies due to their immunity to phase noise, low output power backoff, and adaptive head and tail length adjustment [55]. According to high-performance criteria, the suggested MIMO design is appropriate for a variety of T-Hz band applications, including biomedical applications, security scanning, sensing, IoT, and 6G high-speed wireless communication systems [56]. Several issues must be resolved for T-Hz communication to be successfully implemented in 6G networks. For example, the sensitivity of T-Hz waves to attenuation and scattering [57], which can result in severe signal loss and constrict communication range [58], is one of the major difficulties. To guarantee reliable connection, it is also necessary to improve the hardware needed for T-Hz transmissions, such as the transceivers and antennas [59].

VLC is a high-speed communication system that operates in the unlicensed 400–800 T-Hz frequency band and can be used as an alternate method of resolving communication issues in future networks. This technique entails employing light waves in addition to radio waves to transport data, which can result in faster data rates and better security. The performance of VLC and other optical wireless data transmission methods is thought to be comparable to that of fiber and can range from Gbps to Tbps [60]. Additionally; it is anticipated to offer short-range indoor connectivity, which might boost data rates even further to Tbps [61]. In recent years, VLC in 5G networks has drawn a lot of attention because of its architecture, core technologies, physical-layer security, and performance enhancement [62]. If combined, VLC and RF have the potential to overcome the shortcomings of each medium [63]. For instance, VLC integration is most useful in situations when RF signals are obstructed or attenuated in the underground or inside buildings. In remote areas with poor RF coverage, high-speed Internet access is offered using VLC-RF networks [64]. VLC provides very high-frequency reuse, negligible electromagnetic interference, a wide unlicensed spectrum, and ultrahigh bandwidth (in terahertz) [65]. This inventive component will soon deliver 1-GHz-plus bandwidth, and a single-diode LED has demonstrated about 10 Gbps [66]. Furthermore, VLC has immense potential over the next 10 years to overcome the performance gap with 5G/6G technologies. whereas 5G technology has already delivered gigabits per second [67]. Due to its capacity to function over a wide bandwidth at T-Hz frequencies, VLC is also viewed as a technology that might be able to meet the needs of 6G. The development of micro- and nanotechnology has made it possible for optical wireless data transmission technologies like VLC and others, which have the same potential as Li-Fi in 6G [68].

Key technologies used for RF planning and optimization include O-RAN, mmWave, T-Hz, and VLC which are elaborated in Table 1. An open virtualized and distributed ORAN design enables network operators to dynamically operate their radio access networks. This design allows the radio access network to be dynamically optimized for different user scenarios, as shown in Fig. 2. i.e., mobility, data throughput, latency, and other network-level factors in 6G networks. Overall the Key findings of RF planning and optimization in AI-RAN 6G are as follows:

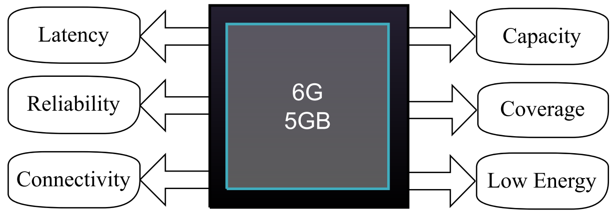

FIGURE 2. Key features of AI-RAN 6G.

- Deep learning can enable accurate and efficient mmWave channel prediction, enabling optimal deployment of mmWave base stations.
- THz communications hold promise for high-bandwidth applications, but their unique propagation characteristics require novel AI-based channel modeling and optimization techniques.
- VLC offers a promising solution for indoor wireless connectivity, and AI can optimize VLC systems for improved performance and coverage.
- mm-Ranger communications, operating at millimeter wavelengths, can provide ultra-high-precision positioning and sensing capabilities, and AI can enhance the accuracy and reliability of these systems.

III. NETWORK CAPACITY AND COVERAGE IN AI-RAN 6G

AI-RAN is a sort of mobile network design that enhances radio access networks using DL techniques. By intelligently managing the radio resources with the help of AI-assisted schemes, AI-RAN can increase the capacity of a mobile network while also improving the user experience. Additionally, AI-RAN can expand coverage by proactively deploying additional base stations to areas with weak signal coverage using predictive analytics. When compared to earlier generations of mobile networks, 6G mobile networks will provide a significant improvement in network capacity and coverage. The capacity of 6G networks is anticipated to be up to 100 times greater than that of 5G networks, and 5G networks are virtually ready to give up to 10 times the capacity of 4G networks.

The application of AI-RAN technology will make it possible to utilize the radio spectrum more effectively and optimize radio resources, leading to an increase in capacity. The 6G networks will have more capacity as well as better coverage. Additionally, several cutting-edge methods are being used by 6G technology to increase coverage, including IRS cells [69], adaptive modulation/coding [70], adaptive/geometrical beamforming [71], AI quantum computing [72], blockchain technology [73], and more. To further increase capacity, 6G technology is also utilizing leading-edge technologies such as massive MIMO [74], mmWave

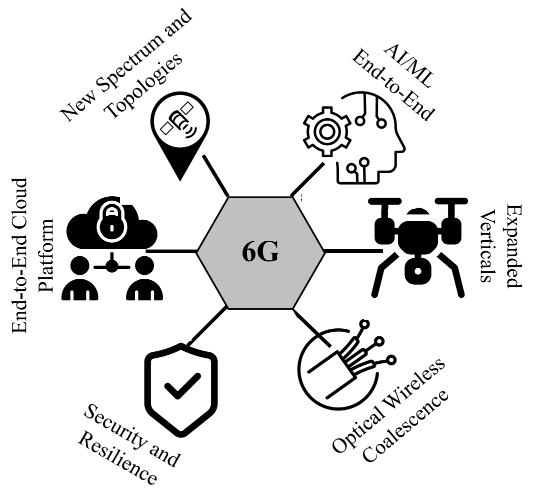

FIGURE 3. Coverage and capacity in AI-RAN 6G.

technologies [75], T-Hz communication [76], VLC [77], and non-orthogonal multiple access (NOMA) [78]. Intelligent networks and services are also enabled by innovative AI-based techniques like machine learning [79], DL [80], and edge computing [81]. Upon utilizing predictive analytics, AI-RAN systems can preemptively deploy more base stations to locations with weak signal coverage. The 6G networks will be able to offer more places and more dependable service by having far more effective coverage than their forerunners. In terms of security, the 6G technology is anticipated to make use of cutting-edge security methods, including quantum cryptography and blockchain technology, to guarantee secure communication.

6G technology is exploring multiple technologies to increase capacity and performance as depicted in Fig. 3. These include Intelligent reflecting surface cells, Adaptive modulation/coding, Beamforming, artificial intelligence, mmWave technologies, T-Hz communication, Visible light communication (VLC), and Non-Orthogonal Multiple Access (NOMA). These technologies are expected to enhance performance and improve the user experience [82]. Additionally, micro- and nano-technology are expected to be important in building high-quality infrastructure for 6G networks [83].

We have already discussed the benefits and applications of mmWave, T-Hz and VLC in the previous section. Here, we will elaborate on some other factors as shown in Table 2 that will be useful to improve capacity and coverage in 6G AI-RAN.

A. INTELLIGENT REFLECTING SURFACES (IRS) CELLS

IRS can be used to improve coverage and signal quality in signal-weak areas by reflecting and rerouting signals. Intelligent Reflecting Surfaces (IRS) are being studied as a potential solution for upgrading wireless communication networks beyond 5G [84], [85]. IRS can improve wireless signal coverage and quality in regions where a direct line of sight to the base station is not practicable or in areas with weak radio signals [86]. IRS devices are made up of a large number of small reflecting elements that can be utilized to amplify or reroute signals [87]. IRS has also looked into a variety of issues, such as the design of the reflecting surfaces and their connection with other network technologies [88]. It has a potential for enhancing future networks that are recently being thoroughly investigated. There few certain future directions, i.e., air interfaces, transmission technologies, network topologies, intelligent materials and devices are required to achieve the main goals of 6G networks [89].

B. ADAPTIVE MODULATION AND CODING (AMC)

AMC schemes are exploited to transmit data in accordance with the channel conditions, which can improve the signal's quality and dependability [90]. It is a technology that can be used in 6G networks to improve the quality and reliability of wireless signals [91]. The signal quality can improve the overall performance of the network by adjusting the modulation and coding schemes according to the current channel conditions. Many techniques have been investigated for modifying the modulation and coding schemes according to the current channel conditions, such as channel state information (CSI), signal-to-noise-ratio (SNR), and bit-error-rate (BER) [92]. Adaptive modulation and coding were previously implemented in LTE and 5G wireless systems and are considered a promising technology for improving the overall performance of 6G networks. CSI refers to information about the channel that is used by the transceivers to optimize the transmission parameters, such as the modulation scheme, coding rate, and power level. It provides information about the strength and quality of the wireless signal, including the presence of interference, multi-path effects, and fading. Furthermore, there is ongoing research exploring different aspects of CSI for 6G networks, such as the acquisition and processing of CSI [93], the impact of channel imperfections on CSI [94], pilot-based & non-pilot-based methods [95] and the use of machine learning techniques for CSI prediction and optimization [96]. The CSI for 6G networks is effective in enabling more efficient and reliable wireless communication in next-generation networks.

C. BEAMFORMING

Beamforming is used in the bi-direction (uplink and downlink) of wireless communications. In uplink communication, the receiver uses beamforming to improve the SNR) of the received signal. This improves BER and channel capacity. In downlink communication, transmitters use beamforming to target specific users or areas of coverage. This improves coverage and reduces interference. Beamforming in 6G is expected to play a key role in achieving high data rates and low latency [97]. 6G networks are exploiting advanced beamforming techniques such as

TABLE 2. Network capacity and coverage key concepts.

Key Concepts	Remarks
IRS cells [69]	It can significantly improve the capacity performance and power consumption of micro-cell base stations, leading in significant energy savings. IRS can also aid in the evolution of 6G radios in the IoT market, as well as in the reduction of energy consumption in future mobile networks.
Adaptive modulation/coding [70]	A novel adaptive modulation and coding (AMC) based threshold Denoised Recurrent Neural Network (TDRNN) is suitable for adaptive coding and modulation in 6G wireless communication systems.
Adaptive/Geometrical beamforming [71]	Although this technology can achieve data speeds of up to 1Tbps, it is still in its early phases of development. Using terahertz frequency technology, researchers have achieved 100 Gbps data rates.
Visible light communication (VLC) [47]	A smart MIMO antenna layout with cutting-edge beamforming algorithms for future wireless networks like 6G and beyond. It delivers efficient directional gain and improved power gain at a low cost and operational simplicity by optimizing phase delay factors at the transmitter. It is proved that beam width and beam steering may be controlled effectively.
AI quantum computing [72]	It is envisioned that quantum computing (QC) will function as crucial enablers and strong accelerators to significantly reduce processing complexities and improve the security of future 6G and beyond communication networks.
Blockchain technology [73]	The unique properties of blockchain for 6G dynamic spectrum sharing (DSS) will be showcased along with key technologies such as self-free massive MIMO and smart contracts that enable automated resource sharing. The use of blockchain in DSS is seen as a promising solution for 6G networks.
Non-orthogonal multiple access (NOMA) [78]	It is seen as a potential multiple access technology for 6G networks, with applications such as smart contracts, power allocation strategies in power domain massive machine-type communication, and hybrid NOMA-assisted mobile edge computing (MEC). NOMA is also seen as a critical technology for future wireless networks and has been studied in a variety of deployment situations.
Machine learning [79]	In comparison to 5G, 6G is intended to achieve a number of extremely severe specifications, including extremely high data rates, extremely wide coverage, extremely low latency, extremely low power consumption, extremely high dependability, exceptionally large connection, and so on. With the above very high criteria for numerous applications, including new combinations of needs for new use cases, AI/ML will play a more vital role than ever in 6G wireless communications.
DL [80]	DL is a promising technology for improving the capabilities, security, and performance of 6G mobile networks.
Edge computing [81]	It is regarded as a critical technology for 6G networks, with the potential to provide low-latency edge intelligence and a wide range of applications.

hybrid beamforming, which combines digital and analog beamforming, and intelligent beamforming, which uses machine learning techniques to optimize the beamforming process based on real-time network conditions. Several beamforming-based techniques are projected to be utilized in 6G networks to improve the efficiency and efficacy of wireless communications. Some main techniques are discussed here:

1) HYBRID BEAMFORMING

It combines digital and analog beamforming to gain the advantages of both. Hybrid beamforming employs a large number of antenna arrays, with digital beamforming used in the baseband and analog beamforming used in the radio frequency (RF) [98].

2) INTELLIGENT BEAMFORMING

It optimizes the beamforming process based on real-time network conditions using machine learning approaches. Intelligent beamforming may dynamically alter beamforming parameters such as beamforming direction, beam breadth, and beam strength by analyzing network data such as user location, traffic patterns, and interference levels [99].

D. ARTIFICIAL INTELLIGENCE (AI)

AI can be utilized in a variety of contexts, such as to enhance radio resource management or optimize networks. AI is being employed in LTE and 5G networks to increase network efficiency and performance. In contrast, AI in LTE is primarily utilized to increase network efficiency and performance through network management and resource allocation. While, AI-based 5G networks have illustrated improved network performance, resource sharing, and operational management [100]. Furthermore, it played a much larger role, particularly in network slicing and predictive maintenance, where AI will be used to dynamically allocate network resources for specific services and applications [101]. AI is expected to perform a significant role in the architecture of 6G networks, building upon the innovations of previous generations and enabling new use cases and applications. In particular, AI is intended to be utilized for network planning, optimization, and self-configuration, as well as for increasing radio resource management and optimizing networks [102]. Furthermore, problem-solving studies are investigating the application of machine learning techniques for optimizing beamforming performance and constructing more intelligent and dynamic wireless networks [103].

E. NON-ORTHOGONAL MULTIPLE ACCESS

NOMA is being researched and developed for usage in the next generation of mobile communication networks like 6G. The 5G networks utilize NOMA, a promising technology. Multiple users being able to access the same time-frequency resource [104] has proved helpful in increasing network capacity [105]. This is especially helpful in congested networks with high user density [106]. NOMA substitutes power-domain multiplexing for conventional orthogonal resource allocation techniques to accomplish this [107]. By lowering latency and increasing data speeds, NOMA can enhance the user experience. Overall, NOMA could be a big step forward for 5G networks in terms of capacity and performance. When compared to 5G, 6G's NOMA comprises resource allocation [108] interference management [109], and the optimization of power and transmission distribution [110]. The integration of NOMA with other technologies, such as millimeter-wave communications [111], Intelligent Reflecting Surface [112], and edge computing [113], as well as the environmental effects/Green Communication [114] of deploying NOMA in mobile communication networks have also been emphasized.

Overall, these technologies are anticipated to boost the 6G networks' performance and capacity, enabling faster and more dependable wireless communication. Additionally, the development of cutting-edge 6G network infrastructure is projected to heavily rely on micro- and nanotechnology. The key findings of network capacity and coverage in AI-RAN 6G are as mentioned:

- IRS cells can significantly enhance network coverage and capacity by intelligently reflecting radio signals, reducing transmission losses during obstacle detection and extending coverage area.
- Adaptive modulation dynamically adjusts modulation schemes based on channel conditions, improving spectral efficiency and maximizing data rates.
- VLC offers a complementary technology to RF communications, providing high-speed, secure data transmission in indoor environments.
- AI quantum computing holds immense potential for network optimization, enabling real-time, complex calculations for network resource allocation and interference management.
- AI-Blockchain technology can enhance network security and transparency, facilitating secure data sharing and trusted network operations.
- NOMA enables efficient utilization of shared spectrum by allowing multiple users to transmit simultaneously, improving network capacity and efficiency with the help of AI.
- Machine learning and deep learning techniques can analyze vast amounts of network data to identify patterns and predict network behavior, enabling proactive optimization and anomaly detection.
- Edge computing brings computation closer to the network edge, reducing latency and enabling real-time decision-making for network optimization.

The AI-driven technologies are poised to revolutionize network capacity and coverage in 6G networks, enabling efficient, high-performance, and secure wireless connectivity for future applications.

IV. MOBILITY AND HANDOVER IN AI-RAN 6G

Mobility and handover are key components of wireless networks that allow continuous communication and service delivery while users move between the cells and networks. Furthermore, to provide seamless and uninterrupted service delivery for users, future networks will use a combination of techniques and methods, i.e., handover decision approaches, small cells, beamforming, and Massive MIMO technology, among others. These techniques are useful to boost network coverage and capacity while reducing interference and improving network performance.

In 5G/6G networks, handover decision techniques are critical in identifying when and which cell, a user should be handed over to provide uninterrupted and high-quality communication [115]. While specific techniques for handover decision-making in future networks are still in the development process, here are some common techniques that can be used for algorithmic design in 5G/6G, i.e., the Received signal strength (RSS) [116], Signal-to-interference-plus-noise ratio (SINR) [117], Quality of Service (QoS) [118] and Hybrid Approach based on SINR, QoS requirements for load balancing to determine the most suitable target cell for handover [119].

Small cells, on the other hand, are low-power base stations that supplement the macro network. It allows users to maintain high data rates even when traveling at fast speeds [120]. The key concepts that are commonly used in mobility and handover are summarised in Table 3.

While in 6G networks, mobility and handover management via beamforming allow efficient and robust communication by enabling seamless handovers, greater mobility support, adaptive beam management, and increased network capacity [121]. 6G networks can provide improved user experiences, higher network performance, and better utilization of network resources in dynamic and mobile contexts by employing advanced beamforming techniques.

Mobility and handover are key components of LTE and 5G networks because they have a direct impact on the user experience and overall network performance. Various strategies for ensuring seamless mobility and handover transitions have been developed. In LTE networks, for example, 'X2-based handover' is used for inter-eNodeB handover, which requires coordination between the relevant eNodeBs [122]. Whereas, for inter-system (3G/2G) handover, 'S1-based handover' is used [123]. Dual Connectivity is utilized in 5G networks, which use both LTE and 5G cells simultaneously to improve handover [124]. In terms of mobility management, the Centralized mobility management (CMM) [125] and Distributed mobility management (DMM) [126] methodologies are widely utilized. The CMM employs a centralized anchor node to keep information and route packets during the mobility process, whereas the DMM enhances the role of the anchor node to perform UE mobility more efficiently. DL techniques are also being investigated for their potential use in optimizing handover and mobility management in LTE and 5G networks [127]. Recently, new solutions have been developed to solve the issues faced by the ultra-dense 5G HetNet [128].

In 6G network handover and mobility management open up new possibilities such as DL, Multi-access edge computing, DL-based intelligent dual connectivity, Dynamic point selection (DPS), AI Mobility-aware resource allocation, Machine learning-based handover decisions, DL-based proactive handover, Fast cell selection & Context-aware handover and Intelligent reflecting surfaces (IRS). Here's a summary of how these technologies can be applied in 6G such as:

- DL: DL techniques in 6G can be applied to different elements of handover and mobility management. DL models can extract patterns from enormous amounts of data, forecast user behavior, and optimize handover decisions [129]. These models are capable of learning complicated linkages and adapting to dynamic network conditions, resulting in improved changeover speed and user experience.
- Multi-Access Edge Computing (MEC): MEC moves computing and storage closer to the network edge, allowing for faster processing and decision-making during handover events. Handover decisions can be made locally using MEC, lowering latency and ensuring real-time responsiveness. It also enables effective resource allocation and content caching, improving overall handover and mobility management performance [130].
- Intelligent Dual connection Based on DL: Intelligent dual connection combines several access technologies, such as 5G and Wi-Fi, to optimize the user experience and handover performance. DL models can be used to determine the best access technology based on real-time network conditions, user preferences, and application needs [131]. This method optimizes handover decisions, increases data speeds, and maintains continuous connectivity.
- Dynamic Point Selection (DPS): Based on real-time network conditions, DPS technique dynamically determines the appropriate communication point for handover [132]. DPS improves changeover performance and maintains high-quality connectivity during mobility by taking into account aspects like signal strength, channel quality, and load balancing.
- AI Mobility-Aware Resource Allocation: It uses AI to optimize resource allocation during handover events are called mobility-aware resource allocation algorithms. To allocate radio resources efficiently, these algorithms analyze user mobility patterns, traffic load, and quality of service requirements. AI-based mobility-aware resource allocation improves network speed and user experience by dynamically modifying resource allocation according to user mobility [133].
- Deep-Learning-Based Proactive Handover: Proactive handover technique anticipates probable handover occurrences based on user movement patterns, network circumstances, and other contextual data [134]. DL models can use these parameters to predict changeover requirements and conduct proactive handover operations, reducing latency and ensuring continuous connectivity.
- Context-Aware Handover and Fast Cell Selection: Context-Aware Handover approaches strive to reduce handover delay by quickly finding the appropriate target cell based on signal quality and

TABLE 3. Mobility and handover key concepts.

Key Concepts	Remarks
Centralized mobility management (CMM) [125] Distributed mobility management (DMM) [126]	Certain existing network-based mobility management systems still experience handover delays, packet loss, and high signaling costs due to changeover processing. The SDN-based GMM technique outperforms traditional handover processes and alternative solutions in terms of handover duration, signaling cost, network performance, and packet loss.
Intelligent dual connection [131]	Intelligent dual connection combines several access technologies, such as 5G and Wi-Fi, to optimize the user experience and handover performance to determine the best access technology.
Dynamic point selection (DPS) [132]	It is useful for network optimization such as handover optimization and real-time network monitoring.
AI mobility-aware resource allocation [133]	Mobility-aware resource allocation algorithms analyze user mobility patterns, traffic load, and adapt based on user mobility.
DL-based proactive handover [134]	It is based on user mobility, network conditions, and other contextual data. DL models can use these metrics to estimate requirements and perform proactive handover operations to minimize latency and ensure continuous connectivity.
Context-aware and Fast cell handover [135]	It is effective to improve handover decisions by considering additional contextual information like user preferences and application needs. These tactics provide smooth handoffs and an excellent user experience.

other parameters. Context-aware handover approaches optimize handover decisions by considering additional contextual information such as user preferences and application needs [135]. These strategies provide seamless handovers and a high-quality user experience.
- Intelligent Reflecting Surfaces (IRS): Intelligent reflecting surfaces are made up of passive reflecting parts that are capable of manipulating wireless signals. They can improve signal strength, coverage, and quality in specific locations by altering the reflection qualities of these surfaces. IRS can be deliberately placed to improve the overall user experience, optimize changeover performance, and assure seamless connectivity [136].

These technologies have the ability to improve network performance, decrease latency, maximize resource consumption, and provide continuous connectivity even in dynamic and difficult circumstances for more intelligent, efficient, and tailored handover and mobility management. he overall key findings of mobility and handover in AI-RAN 6G are as follows:

- Centralized and distributed mobility management architecture can effectively handle the increased complexity of 6G networks, enabling optimized mobility decisions across a wide range of network entities by using deep learning based on large data training.
- Intelligent-based dual connection techniques allow user equipment (UE) to maintain simultaneous connections to multiple base stations (BSs), enhancing network resilience and improving user experience.
- Dynamic point selection algorithms intelligently select the best point of attachment (PoA) for UEs, optimizing network performance and reducing handover overhead.
- AI mobility-aware resource allocation techniques consider UE mobility patterns and network conditions, ensuring efficient resource allocation and maximizing network throughput.
- DL-based proactive handover techniques leverage deep learning algorithms to predict handover events before they occur, minimizing handover latency and improving user experience.
- Context-aware handover considers UE-specific information and network context, enabling personalized handover decisions that optimize performance and user experience.
- Fast cell handover techniques minimize handover duration, ensuring seamless connectivity and

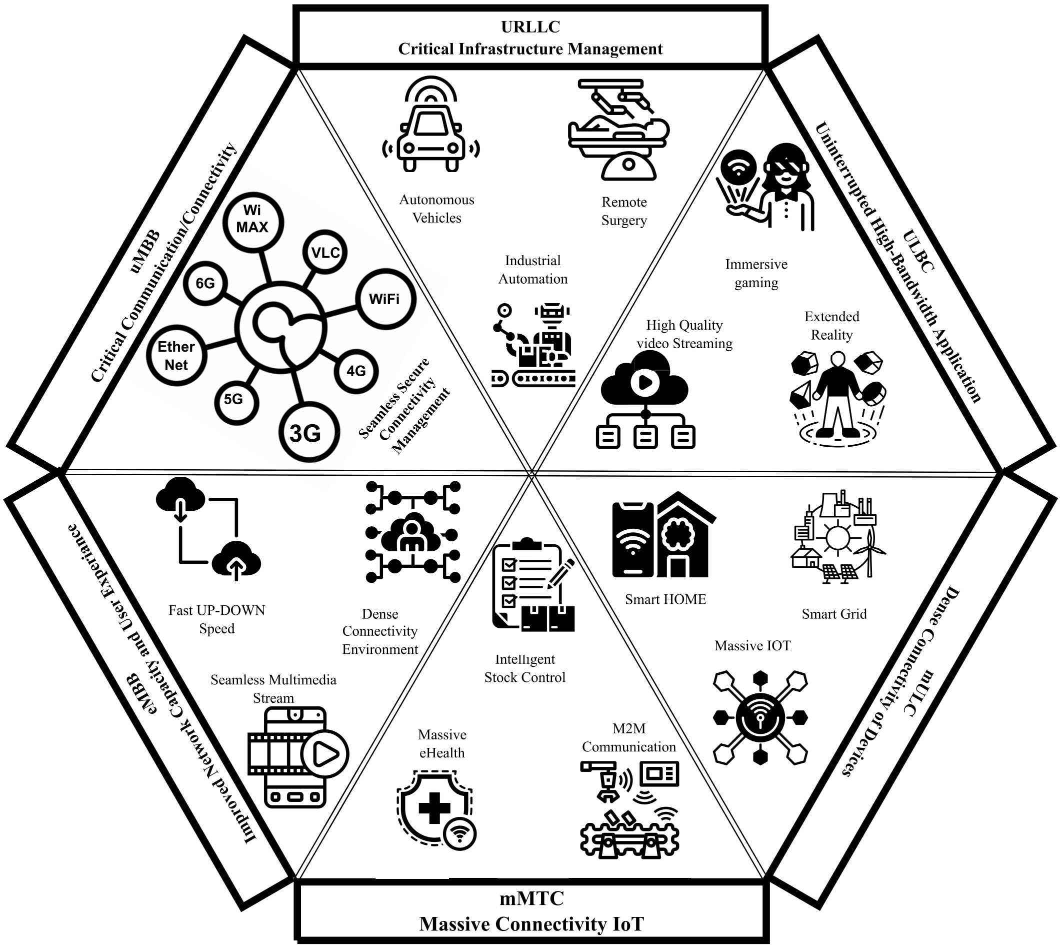

FIGURE 4. 6G AI-RAN use cases.

uninterrupted user experience even in high-mobility scenarios.

The AI-driven mobility and handover management techniques play a crucial role in enabling seamless, efficient, and intelligent mobility support in 6G networks, making provision for next-generation wireless services and applications.

V. AI-RAN 6G USE CASES

AI is playing a crucial function in the RAN 6G networks, allowing new capabilities and enhancing network performance. AI-RAN with each of the use cases as recapped in Table 4 is in its early stages. However, by leveraging sophisticated technologies and capabilities, AI-RAN has made tremendous progress in different use cases of 6G networks as shown in Fig. 4. Here are some potential AI-RAN in 6G network use cases alike.

1) ULTRA-RELIABLE LOW LATENCY COMMUNICATIONS (URLLC)

URLLC intends to deliver mission-critical applications with ultra-reliable connectivity with extremely low latency. AI-RAN, which employs intelligent resource management and optimization approaches, plays a critical role in attaining this. AI-driven mechanisms are being developed by researchers to dynamically allocate network resources based on real-time demands, ensuring high reliability and low latency [137] for critical applications such as autonomous vehicles, industrial automation, emergency response, public safety, and remote surgery/diagnosis [138]. To provide continuous and reliable communications, AI-RAN system assesses network conditions, identifies congestion, and proactively optimizes resource allocation.

2) ULTRA-RELIABLE LOW LATENCY BROADBAND COMMUNICATION (ULBC)

ULBC applies the requirements for dependability and low latency to broadband communication services. Researchers are investigating AI-based methods to improve the performance of ULBC, such as traffic prediction, network slicing, and intelligent beamforming [139]. ULBC can dynamically adapt to network conditions, predict user demand patterns, and optimally allocate resources by employing AI-RAN to ensure smooth broadband access with high reliability and low latency. This enables applications like high-definition video streaming, virtual reality, and augmented reality experiences to run

TABLE 4. Use cases key concepts.

Key Concepts	Remarks
URLLC [125], [126]	It is a key concept in 6G networks for dynamically distributing network resources based on real-time demands for mission-critical applications such as driverless vehicles, industrial automation, and emergency response. By monitoring network conditions, recognizing congestion, and optimizing resource allocation, AI-driven procedures are being created to provide high reliability and low latency.
ULBC [127], [128]	It is a concept that improves the performance of broadband communication services by applying dependability and low latency needs such as traffic prediction, network slicing, and intelligent beamforming. ULBC can handle applications such as high-definition video streaming, virtual reality, and augmented reality experiences, as well as applications that require both URLLC and high throughput.
mULC [129], [130]	It provides ultra-reliable, low-latency connectivity for massive Machine-to-Machine (M2M) communications in the IoT industry. It is often used for intelligent device identification, automated anomaly detection, and dynamic spectrum allocation to ensure trustworthy and time-sensitive connectivity for smart cities, industrial IoT, and environmental monitoring.
eMBB [131], [132]	It aims to improve mobile broadband experiences by increasing data speeds, capacity, and ensuring seamless connectivity. Customers can now enjoy high-quality multimedia offerings, interactive gaming, and uninterrupted connectivity even in densely populated places or at crowded events.
uMBB [133], [134]	This guarantees seamless and low-latency broadband connectivity, supporting digital inclusion and enabling a variety of applications.
mMTC [135],[136]	It is intended to satisfy the connectivity requirements of large-scale IoT deployments with a high device density. It is often used to evaluate device behavior, traffic patterns, and network conditions in order to dynamically distribute resources, optimize power utilization, and ensure IoT device communication is efficient and dependable.

smoothly and quickly [140]. Furthermore, ULBC enables applications that demand both URLLC and exceedingly high throughput.

3) MASSIVE ULTRA-RELIABLE LOW LATENCY COMMUNICATION (MULC)

The goal of mULC is to provide ultra-reliable and low-latency connectivity for enormous M2M communications in the IoT sector. AI-RAN allows for the effective administration of a large number of devices, network resources, and data traffic patterns [141]. To provide reliable and low-latency connectivity for a large number of IoT devices, researchers are studying AI-driven solutions for intelligent device authentication, automated anomaly detection, and dynamic spectrum allocation [142]. AI-RAN improvements guarantee dependable and time-sensitive connectivity for applications such as smart cities, industrial IoT, and environmental monitoring.

4) ENHANCED MOBILE BROADBAND (EMBB)

eMBB seeks to improve mobile broadband experiences by providing greater data speeds, increased capacity, and seamless connectivity. This use case is aided by AI-RAN, which employs a machine learning approach for intelligent spectrum management, interference reduction, and user experience optimization [143]. eMBB can dynamically adapt to changing user demand and network conditions by enabling AI-driven network optimization, optimal resource allocation and better spectral efficiency [144]. This enables customers to experience high-quality multimedia services, interactive gaming, and continuous connectivity even in densely populated areas or during packed events.

5) UBIQUITOUS LOW LATENCY BROADBAND COMMUNICATION (UMBB)

The goal of uMBB is to provide ubiquitous broadband access with low latency for a variety of applications and scenarios. By integrating DL approaches for traffic prediction, user behavior analysis, and network optimization, AI-RAN enables intelligent network planning and deployment. AI-based solutions are being developed by researchers to dynamically alter network coverage, optimize resource allocation, and reduce latency in a variety of situations, including rural areas, transit systems, and public venues [145]. AI-RAN advances for uMBB guarantee seamless and low-latency broadband connectivity, supporting digital inclusion and enabling a variety of applications [146].

6) MASSIVE MACHINE TYPE COMMUNICATION (MMTC)

mMTC is designed to meet the connection needs of large-scale IoT with a high density of connected devices. AI-RAN is critical to efficiently managing the large flooding of devices and different traffic patterns. To address the connection demands of mMTC, researchers are investigating AI-driven solutions for intelligent device onboarding, scalable network slicing, and efficient access management [147]. AI-RAN systems evaluate device behavior, traffic patterns, and network circumstances to dynamically distribute resources, optimize power usage, and ensure the efficient and reliable communication of IoT appliances [148].

AI-RAN research is paving the way for many use cases in practical 6G network implementation. AI-RAN enables ultra-reliable, low-latency and broadband communication for critical applications likely massive IoT deployments, and enhanced user experiences by leveraging the power of DL. Additionally, shaping the future of wireless networks and transforming multiple industries.

VI. AI-RAN 6G OPPORTUNITY AND CHALLENGES

Indeed, the development of AI-RAN for 6G networks presents a range of opportunities and challenges. Let's discuss the some of important aspects:

A. OPPORTUNITIES

1) ENHANCED NETWORK PERFORMANCE

AI can optimize the allocation of network resources, dynamically adapt to changing network conditions, and improve overall network performance. It can enable efficient spectrum management, intelligent beamforming, and advanced interference mitigation techniques, resulting in higher data rates, lower latency, and better quality of service for users.

2) INTELLIGENT NETWORK MANAGEMENT

AI can enable self-organizing networks that can autonomously monitor, analyze, and optimize network operations. It can detect anomalies, predict failures, and proactively take corrective actions, leading to improved network reliability, fault tolerance, and reduced maintenance costs.

3) ENERGY EFFICIENCY

AI approach can optimize power consumption by intelligently controlling network components based on real-time traffic patterns. This can result in energy-efficient operations, reduced carbon footprint, and cost savings for network operators.

4) INTELLIGENT EDGE COMPUTING

AI-enabled RAN can support edge computing capabilities, allowing for faster analysis and processing of data at the network edge. This enables low-latency applications, such as real-time video analytics, augmented reality (AR), and virtual reality (VR), enhancing user experiences and enabling new services.

5) ENHANCED NETWORK SECURITY

AI can be used to detect and mitigate security threats in real-time, improving the overall security of the 6G network. AI can be used to develop more secure network devices and applications. For example, AI-powered intrusion detection systems can be used to protect devices from unauthorized access and malicious software. AI can also be used to develop more secure authentication and authorization mechanisms.

6) ADVANCED NETWORK AUTOMATION

AI in 6G can automate various network management tasks, such as network planning, configuration, and optimization, reducing the need for manual intervention and improving operational efficiency. It could be used to develop more efficient and effective network planning algorithms. For example, AI can be used to predict traffic demand and allocate resources to identify and optimize network bottlenecks. Furthermore, AI is effective in automating the configuration of network devices and services. This can help to reduce errors and improve the consistency of network configurations. AI is also helpful in optimizing network performance and efficiency. For example, AI can be used to adjust routing tables to minimize latency, or to optimize resource allocation to improve throughput.

B. CHALLENGES

1) COMPLEXITY AND SCALABILITY

Implementing AI in RAN introduces complexity due to the large amount of data generated, increased computational requirements, and the need for advanced techniques. Scaling AI-enabled RAN to support a massive number of devices and users poses significant technical challenges.

2) DATA PRIVACY AND SECURITY

AI relies on extensive data collection and analysis, which raises concerns about privacy and security. Safeguarding user data, preventing unauthorized access, and ensuring transparent data usage and storage practices become critical considerations.

3) REGULATORY AND ETHICAL ISSUES

The use of AI in RAN requires careful attention to regulatory compliance, transparency, and fairness. There is a need to address potential biases in algorithms, ensure transparency in decision-making processes, and establish guidelines for responsible AI usage.

4) READINESS NETWORKS

The deployment of AI-enabled RAN requires skilled professionals with expertise in AI, network architecture, and data analytics. Building a competent workforce and ensuring their readiness to handle AI-driven technologies can be a significant challenge.

It is crucial to address these challenges by using opportunities presented by AI-RAN in 6G networks. Collaboration among industry stakeholders, policymakers, and researchers is necessary to navigate these complexities and enable DL in future network deployments.

CONCLUSION

AI-RAN has a significant impact on future-generation networks. AI-RAN improves 6G RF planning and optimization by using DL approaches to efficiently distribute radio resources, predict traffic patterns and optimize network performance. AI techniques have the ability to self-adjusting factors like antenna tilting, beamforming, and power regulation, i.e., by evaluating massive quantities of data to improve signal quality, reduce interference, and increase overall network efficiency. Furthermore, 6G AI-RAN network-based coverage and capacity management enables dynamically assigning of resources based on real-time demand, ensuring maximum service quality while minimizing congestion. AI-RAN systems can predict user behavior, identify coverage gaps, and alter network parameters dynamically to ensure seamless connectivity and effective resource consumption. AI-RAN 6G use cases investigate the possible uses of AI in a variety of industries, including smart cities, autonomous transportation, remote healthcare, augmented reality, and vice versa. Artificial intelligence allows advanced functions such as real-time video analytics, predictive maintenance, intelligent traffic management, and tailored services, revolutionizing industries and enhancing the standard of life.

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