

A Comprehensive Introduction to Artificial Intelligence Techniques for Advanced Wireless Networks: 5G and Beyond

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Abstract

The fast development of wireless communication technologies, especially the move to the next generation of 6G wireless networks, has encouraged the demand for smart, flexible, and competent system design. Artificial Intelligence (AI) has become a game-changing enabler, providing robust solutions to handle the high level of complexity and dynamics in advanced wireless networks. This review paper introduces an in-depth overview of how AI methods can be used in the planning, optimization, and operation of 5G and beyond wireless networks. It offers a systematic inference about the incorporation of various AI approaches into major frameworks such as resource distribution, mobility management, network slicing, interference avoidance, and predictive maintenance. Moreover, the article discusses the difficulties associated with the application of AI-driven architectures in practice, pointing out concerns regarding data privacy, the interpretability of the models, computational load, and scalability. The review also presents emerging research directions and open challenges, aiming to provide researchers and practitioners with a foundational understanding of the integration of AI and next-generation wireless communication systems.

Keywords: Artificial Intelligence, Machine Learning, 5G Networks, Deep Learning, Network Optimization.

1. Introduction

Wireless communication has experienced amazing changes and every generation has brought up new possibilities and extended the horizons of connectivity. The 5th generation (5G) of wireless networks has provided enormous changes in data rate, latency, reliability and

network capacity which allow a broad spectrum of applications including enhanced mobile broadband (eMBB), massive machine-type communications (mMTC) and ultra-reliable low-latency communications (URLLC) [1]. But with the rising complexity of these systems, and in light of the intensified requirements of edge-connectivity, mobile reconfiguration and intelligent service delivery, new challenges have emerged that have dwarfed the conventional methods of network designs and management. The evolution of cellular mobile communications is shown in Figure 1.

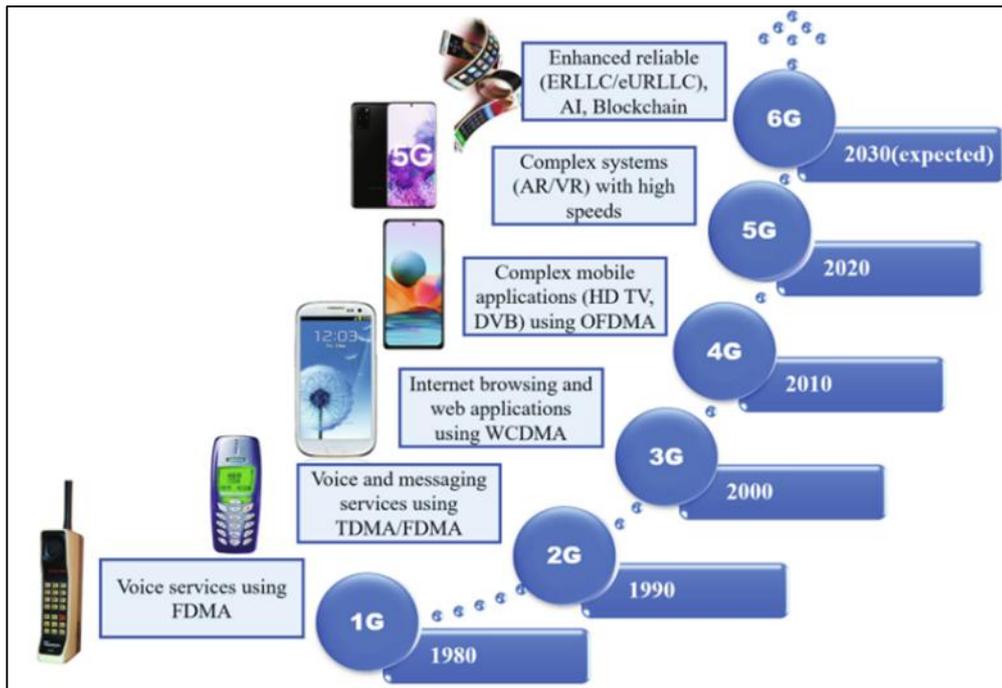


Figure 1. Evolution of Cellular Mobile Communications [2]

In order to address these issues, AI has emerged as a key enabler of advanced wireless networks. AI methods provide potent capabilities in creating models based on data, prediction outcomes, and automation of decision-making procedures, which are crucial for the efficient operations of dynamic and complex network ecosystems. Unlike traditional algorithmic solutions, AI-based mechanisms can adjust to unpredictable and dynamic network circumstances, dynamically allocate resources in real-time, and enable a self-regulating network to operate autonomously. This ability is even more significant, as networks develop toward 6G, which anticipates completely intelligible, situation-sensitive and self-optimizing communication systems [3]. An illustration of 5G networks presented in Figure 2.

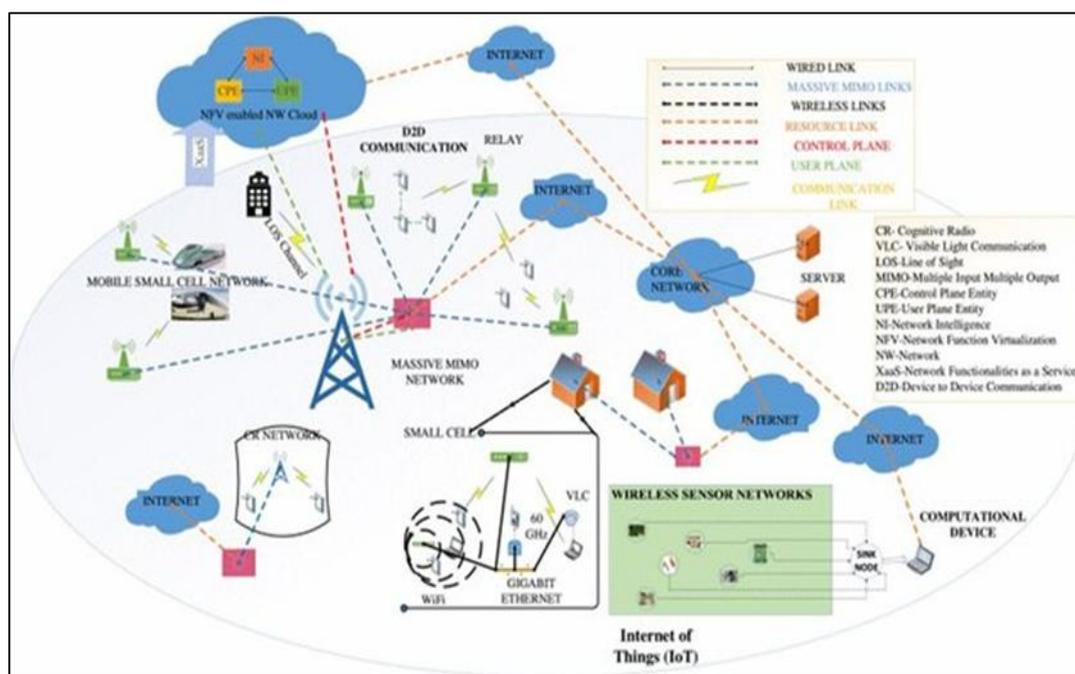


Figure 2. Illustration of 5G Networks [4]

An overview of the implementation of AI techniques in 5G and beyond wireless networks is represented in this review. It addresses the usage of different AI approaches such as machine learning (ML), deep learning (DL), reinforcement learning (RL), and federated learning (FL) in the major functional areas of wireless communication [5]. These areas include spectrum management, traffic forecasting, beamforming, handover, energy efficiency, network slicing, and quality of service (QoS) guarantee. In addition, the review discusses the working architecture that supports the implementation of AI in network infrastructures, which include edge computing, cloud-native architecture, and software-defined networking (SDN). This article takes a critical look at the real-world issues that make it difficult to adopt AI-based solutions, in addition to the benefits that come with their use. These issues involve the problems of data access and secrecy, the interpretability of the models, the complexity of computing, the latency requirements, as well as the standardized interfaces. The intersection of AI and communications networks presents abundant opportunities for innovation and research as the wireless world continues to evolve. Through an integration of emerging trends and the identification of research gaps, the present review article can be viewed as a conceptual resource for exploring and contributing to the ongoing intelligent transformation of wireless networks in the context of 5G and beyond.

2. 5G and Beyond: Overview

The 5G wireless communications constitute a significant breakthrough in mobile networks; it is expected to support the needs of eMBB, URLLC, and mMTC. On the foundations of these pillars, the path to beyond 5G (B5G) and the 6G networks envisages a hyper-intelligent, hyper-connected environment, using communication infrastructure to enable new, unseen data rates, pervasive connectivity, exceptionally high reliability, as well as the intelligence of network behavior [6]. This development has unimaginable potential; at the same time, it presents a novel set of technical and operational issues. Figure 3 summarizes the comparison between 5G and 6G.

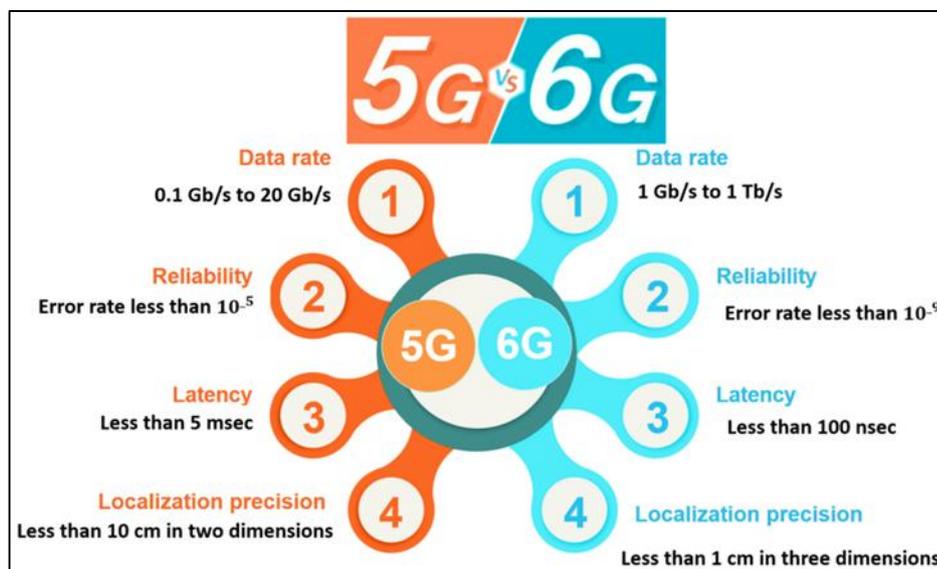


Figure 3. 5G vs 6G [17]

The most outstanding technologies of 5G networks are massive MIMO, millimeter-wave (mmWave) frequencies, beamforming, and network slicing. These characteristics allow for the highest data rates of 10 Gbps, latency of 1 ms, and the connection of 1 million devices per square kilometer. Further innovations planned as we transition to B5G/6G include Terahertz (THz) communication, reconfigurable intelligent surfaces (RIS), non-terrestrial networks (NTN), and integrated sensing and communication (ISAC), which are likely to transform the wireless environment. The improvements are expected to provide even higher rates of data transfer, latency in microseconds, as well as global connectedness. Figure 4 illustrates the service.

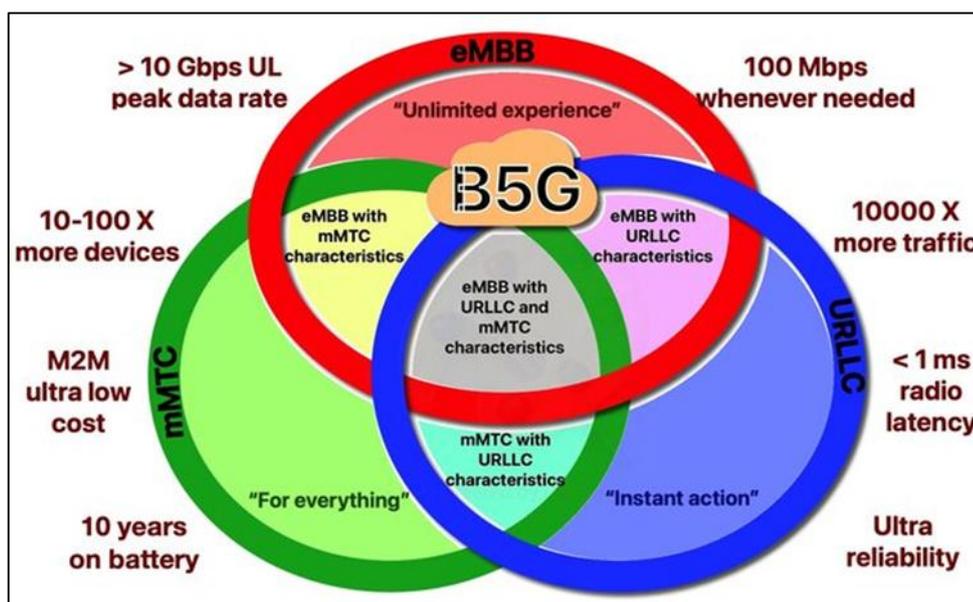


Figure 4. 5G and B5G Service Categories [7]

The uses of 5G and B5G wireless networks are diverse and include revolutionary potential across industries. In the medical industry, low-latency, high-speed connections empower practitioners to conduct remote diagnostic processes, perform surgeries with the help of robots, and monitor patients constantly, making medical services more beneficial and accessible. In transportation and automotive, 5G/B5G enables connected and autonomous vehicles, vehicle-to-everything communication in real-time, and intelligent road traffic systems that can make roadways safer and free of congestion. Industry 4.0 encompasses smart manufacturing, predictive maintenance, and real-time industrial operations control, giving the concept immense power, with B5G technologies making the industry highly automated as functional operations become more efficient. Such high bandwidth, essential in the entertainment sector based on ultra-high and low latency configurations, allows for cloud gaming, augmented reality (AR), virtual reality (VR), and immersive multimedia experiences, creating a new interactive theater for users and content in the sector. In addition, first responders and emergency management can utilize real-time monitoring, communication systems, and improved situational awareness, facilitating more brief and organized response operations during critical incidents. All these applications demonstrate how 5G and B5G networks will transform many spheres of modern life, offering smart, reactive, and high-performing connectivity.

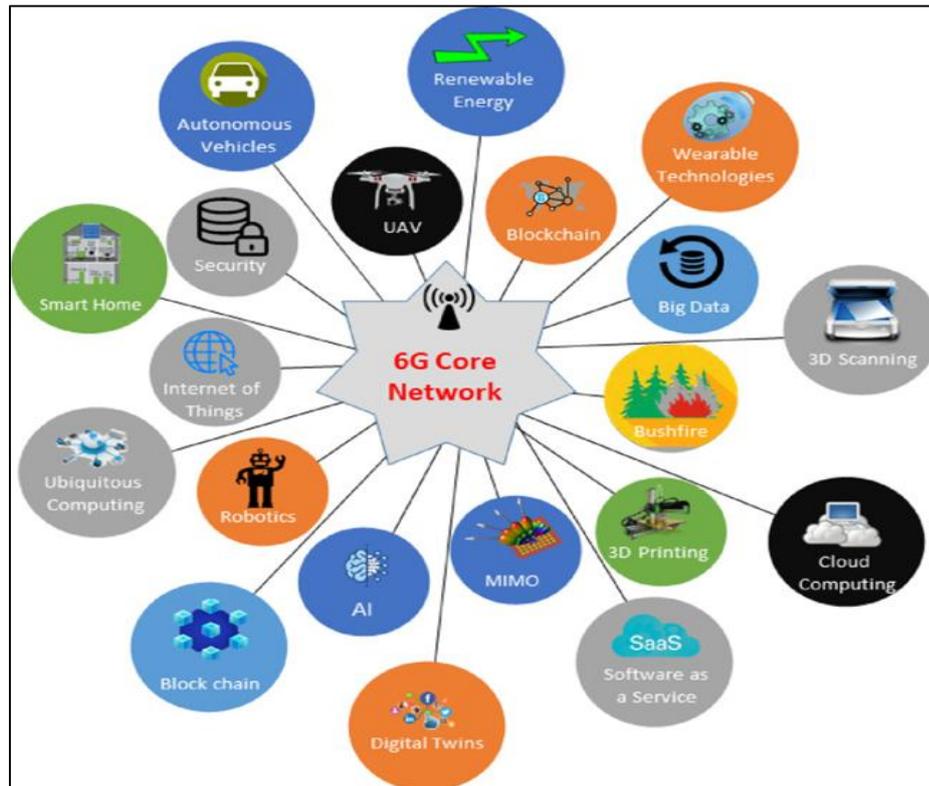


Figure 5. 6G based Applications [9]

B5G presents an opportunity for a revolution in industries. It will support fully autonomous cars, remote surgery in real-time, extended reality (XR), and mass automation of industry with its ultra-high capacity and low latency. In addition, AI and edge computing enable local data processing and intelligent decision-making that does not rely on a centralized data center but is much more responsive. B5G networks will also have the opportunity to provide smart city development, precision agriculture, and next-generation IoT systems with self-organizing and self-healing capabilities. The above figure 5 represents the 6G network based applications and their uses. The implementation of 5G and the creation of B5G networks face significant challenges regarding simplicity. These include high infrastructure costs, energy use, spectrum shortages and heterogeneous interoperability. Another issue is the possibility to maintain a high level of security and data privacy of billions of connected devices, including the integration of AI and cloud technologies. Moreover, handling performance regarding networkability, scalability, and reliability, while upholding quality of service across a variety of applications, is a consistent challenge.

The 5G and beyond wireless networks have the potential to introduce new possibilities that will redefine connectivity across all sectors. Nevertheless, to fulfill their potential, it is

necessary to find unique solutions, interdisciplinary cooperation and thoughtfully approach technical, economic, and regulatory obstacles.

3. Overview of AI Techniques

AI has a broad range of computational practices that allow computers to act similarly to humans in terms of making decisions, learning, and reasoning. Within the framework of advanced wireless networks, AI techniques are essential for introducing the required intelligence to cope with increasingly complex and dynamic environments with the best performance and efficiency and a reasonable level of adaptability. The second part gives a brief introduction to some of the most relevant key AI techniques for 5G and beyond wireless systems key AI techniques: ML, DL, RL and FL, among others. Figure 6 represents AI technology fields.

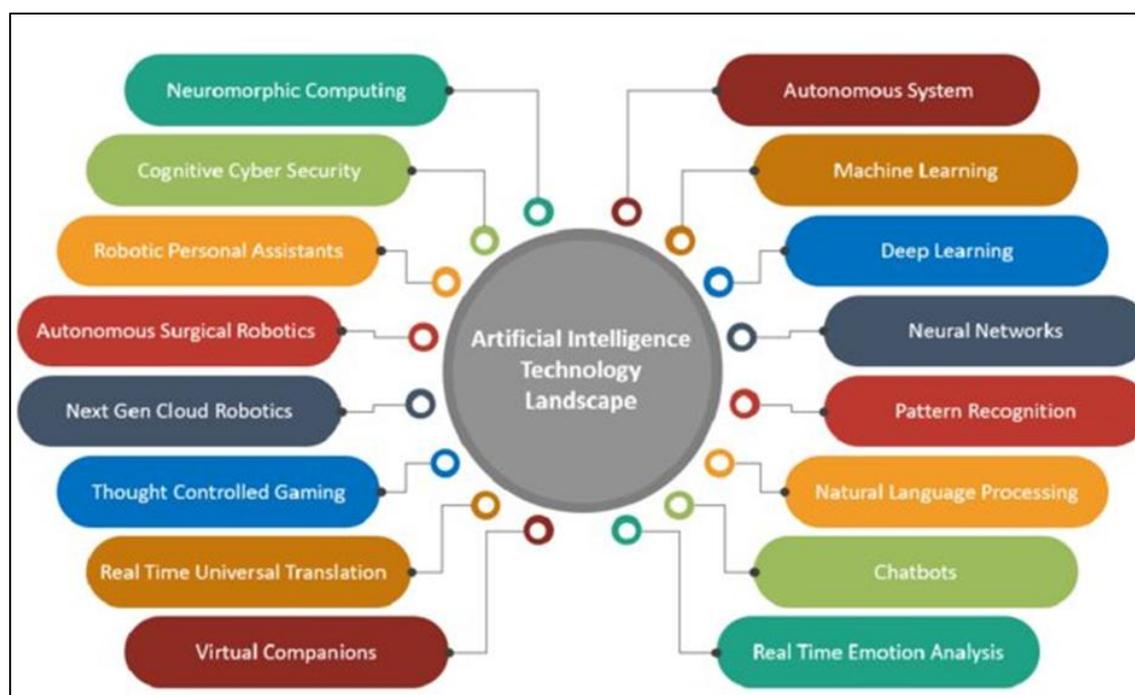


Figure 6. AI Technology Regions [10]

ML: ML is a branch of AI devoted to the learning of algorithms to recognize patterns in the data and become more efficient over time without explicit programming. ML can be broadly grouped into three classes, namely supervised learning (SL), unsupervised learning (USL), and semi-supervised learning (SSL). In a wireless network, SL applications can be found in tasks like traffic classification, channel estimation, and signal detection, in cases where labeled data is available. USL can be used for clustering users, anomaly detection, and developing usage patterns without the use of labeled data. SSL unites the two paradigms with

the purpose of enhancing the overall precision of the learning process when it is difficult to obtain a substantial amount of labeled information.

DL: A narrower subset of ML is known as DL; DL models complex relationships in high-dimensional data using multi-layered neural networks, and other related structures. DL methods, especially Convolutional Neural Networks (CNNs), Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks, have made impressive media attention by achieving high accuracy in image recognition, time series prediction and modeling of sequential data [11]. DL is used in prediction to anticipate congestion within the network, interference detection, beamforming optimization, and intelligent recognition of modulations in wireless systems. The generalization capacity of deep networks to handle large and noisy data makes them very competent in adapting to the highly changing nature of wireless environments.

RL: Another subset of AI is RL in which agents become more competent in decision-making by interacting with an environment to maximize a reward signal. Unlike SL, RL does not assume the availability of labeled datasets; instead, this learning approach employs trial-and-error exploration. RL has emerged as an important solution in wireless communication for dynamic resource allocation, power control, spectrum access, and handling mobility. Methods such as Q-learning and Deep Q-Networks (DQN) can lead to the self-programming of networks in response to changing conditions, resulting in autonomous and intelligent behavior.

FL: FL represents one of the distributed methods of ML, whereby several devices or nodes in the network can collaboratively train a common model without sharing data from local devices with a central node. The strategy is highly applicable in 5G and 6G networks, where privacy, latency and bandwidth are of utmost importance. Being on-device intelligent and group-friendly (enabling edge computing), FL is favorable for use in personalized services and anomaly detection, as well as distributed network control.

Other Techniques: Other AI techniques that are also relevant in the process of optimizing wireless systems include fuzzy logic, genetic algorithms, and support vector machines (SVM). They are usually complemented by the previously described techniques to raise prediction accuracy, flexibility, and reliability in unpredictable circumstances.

The use of these AI methods within wireless communication systems will allow for smarter decisions, dynamic control, and forecast-based upkeep. The application of AI will be essential for providing real-time behavior, scalability, and self-operation of 5G and beyond with more heterogeneous and decentralized networks.

4. AI Applications in 5G and B5G Wireless Networks

The inclusion of AI in 5G and B5G future wireless networks has transformed the way future communication systems are formed, controlled, and optimized. Rule-based systems have become obsolete due to the increasing complexity of network environments, as well as the escalating requirements for high data rates, ultra-low latency, massive connectivity, and real-time flexibility. AI-based models, with their ability to derive knowledge through dynamic input and make smart decisions, present an exceptional alternative. In this section, the essential uses of AI in different layers and segments of 5G and B5G wireless networks are considered. Figure 7 shows AI applications in 5G.

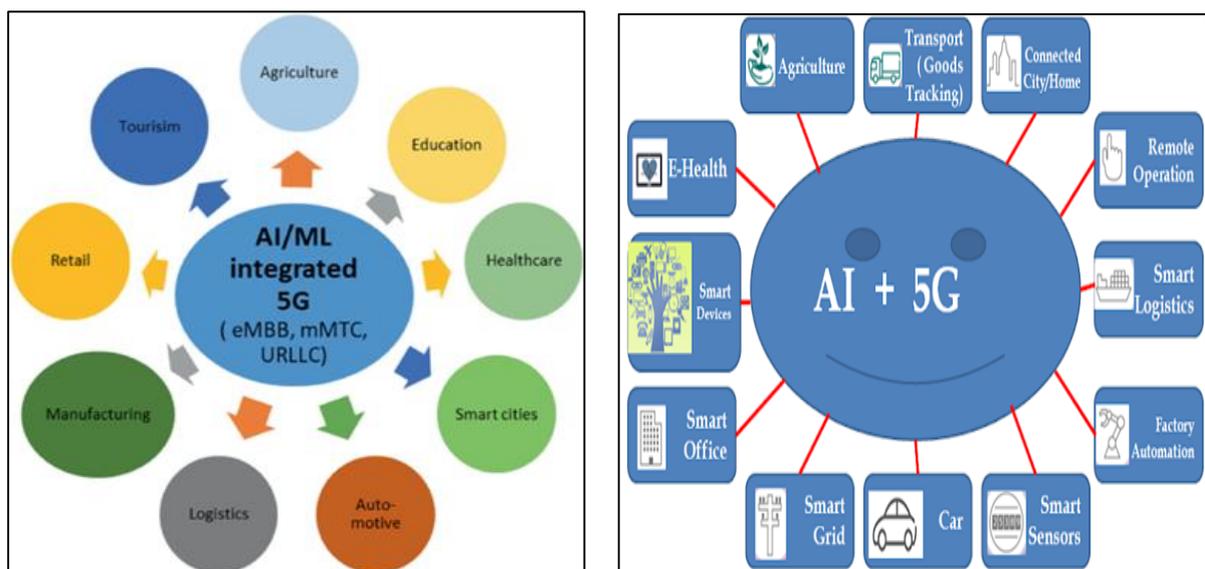


Figure 7. AI Applications in 5G [12]

Intelligent Resource Management: AI has been extremely important in resource-efficient wireless network management by utilizing wireless network resources such as spectrum, power, and bandwidth. Dynamic spectrum allocation, power control, and user scheduling, approaches are optimised through machine learning and reinforcement learning algorithms. These algorithms examine real-time traffic as well as channel states to make aggressive decisions aimed at enhancing spectrum usage and QoS guarantees. With different use cases in a B5G network, such as immersive VR and autonomous vehicles, resource

management must be controlled by AI to support this heterogeneity and a diverse set of service demands.

Network Slicing and Orchestration: Network slicing is considered a critical capability of 5G and B5G networks, with the ability to deploy a variety of virtualized and modified networks on a shared physical infrastructure. Automation of slice creation, resource allocation across slices, as well as real-time orchestration, is achieved through the use of AI techniques. DL models also help predict traffic requirements and adjustments of slice configuration based on user behavior and service-level agreements (SLAs). In addition, AI enables closed-loop automation in network function virtualization (NFV) and SDN, allowing the network to be managed agilely and autonomously. **Mobility and Handover Management:** Ensuring smooth handover among mobile terminals is the most vital issue in 5G and B5G networks, particularly with the spread of high-speed vehicular communications and drones. AI models forecast mobile user locations, attenuation changes, and possible connection interruptions. RL algorithms work to dynamically optimize handover decisions, minimizing latency and other issues. These smart systems improve user experience by ensuring service continuity and network reliability.

Beamforming and Massive MIMO Optimization: Massive MIMO and beamforming are the key technologies in 5G /B5G that allow for higher spectral efficiency and capacity [13]. AI is used to predict channel state information (CSI), design beam patterns freely, and steer beams to users in real-time. The environment-specific behavior of propagation is more complicated and can be learned using supervised learning and deep reinforcement techniques to make beam selection and interference mitigation more effective.

Threat-Detection and Security: As the number of connected devices and open network architectures rise, the issue of security becomes critical in 5G and B5G networks. The application of AI in identifying threats allows for proactive and prevention by identifying anomalies, unauthorized access patterns, and cyberattacks in real-time. Large logs and network traffic can be analysed using DNNs, SVM, unsupervised clustering algorithms to detect intrusion and identify malware. AI also enhances security through privacy-preserving mechanisms that apply federated learning to protect sensitive user data.

Network Analytics and Quality of Experience (QoE): The role of AI in Quality of Experience (QoE) assessment and optimization is to use data on user behavior, service performance, and context. Predictive models are useful for predicting service degradation and proactively allocating resources. In the case of end-user networks, AI-based real-time analytics can help determine network bottlenecks, enabling timely and proactive intervention, thereby increasing end-user satisfaction.

Fog and Edge Intelligence: B5G networks are distributed, and this factor signifies the requirement for localized intelligence at the edge of the network. There is on-device learning and edge inference, enabling applications that need ultra-low latency, e.g., industrial automation, AR, connected vehicles, etc. At the edge nodes, FL and lightweight AI models are used for local data processing and decision-making, reducing reliance on centralized cloud servers. The development of AI has been significant in the transition of 5G and B5G wireless networks into smart, self-adaptive, and self-optimizing networks. From the operation of core networks to the optimization of communication systems to meet the demands of users, AI can assist in such communication systems by satisfying their requirements reliably and efficiently. With the further development of these technologies, the convergence of AI and wireless communication will become the concept of future super-integrated societies.

5. Integration with Emerging Wireless Paradigms

The world of communication is rapidly transitioning into the next generation, where many emerging wireless paradigms are defining their vision of future networks, including 6G. The objectives of these paradigms are to provide ultra-reliable, low-latency, energy-efficient, and context-aware services that integrate more diverse and demanding applications. AI is set to become a focal point in the design, implementation, and maintenance of these new-generation paradigms. The former will discuss the integration of AI with some of the major new wireless technologies such as THz communication, RIS, NTN, and Cell-Free Massive MIMO, which enhance their potential and overcome their limitations. Enabling technologies of 6G are shown in Figure 8.

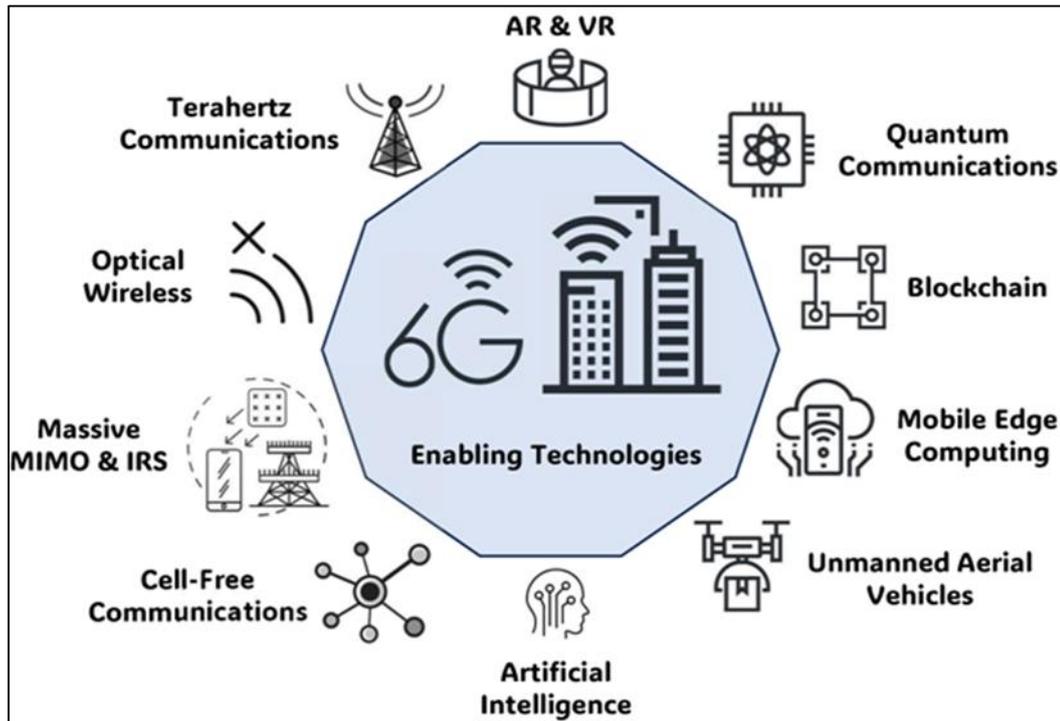


Figure 8. Enabling Technologies [14]

Communication over Terahertz (THz): Designers see THz communication supporting 6G because it is expected to provide very high bandwidth and can support terabit-order data rates. Nonetheless, THz signals encounter serious propagation issues such as high path loss, molecular absorption, and a limited range. Real-time learning of propagation characteristics with AI could be an important factor in addressing these challenges by maximizing channel estimation, beam alignment, and handover processes. Machine learning can also be used to predict the optimum frequencies and tune parameters dynamically in order to sustain the quality of links and thereby enhance the reliability and efficiency of THz communications [15].

Reconfigurable Intelligent Surfaces (RIS): RIS is a new technology that allows manipulation of wireless signal propagation by rationally modifying the reflection and refraction properties of electromagnetic waves. The capability of rearranging such signal paths dynamically with these programmable metasurfaces has the potential to create better coverage, increased capacity, and energy efficiency. Artificial intelligence methods are necessary for controlling the complex optimization of RIS configurations. DL and RL can model and predict the interaction between RIS elements and the environment in dynamic settings so that they can be reconfigured, in real-time and adaptively to operate optimally.

Non-Terrestrial Networks (NTNs): NTNs, such as satellite communications and High-Altitude Platform Systems (HAPS) also bring wireless connectivity to frontiers and underserved areas. Propagation delay, dynamic channel conditions, and resource constraints are some of the problems that are resolved by the implementation of AI in NTNs. AI-enabled solutions will optimize the allocation of satellite beams, dynamic link adaptation, and autonomous routing. Also, predictive analytics will be possible regarding earlier network planning and service preparation in a space-based architecture, deploying a more intelligent and responsive NTN experience.

Cell-Friendly Massive MIMO: In contrast to conventional cellular networks, cell-free massive MIMO is a multi-cellless cellular system that deploys a wide range of distributed antennas to serve users cooperatively in a cell-less architecture. In this paradigm, complex coordination and dynamic user association strategies will be required. AI algorithms will assist in real-time channel analysis, customer grouping, and interference management. Aided by distributed learning and adaptive optimization, AI achieves this efficiently, using network resources as effectively as possible, minimizing latency and maximizing coverage.

Smart Reflecting and Sensing Integration: In the future, communication is likely to be accompanied by sensing, thus resulting in integrated sensing and communication (ISAC). AI methods allow multi-modal data to be combined, which enables networks to perceive the environment and identify patterns to change communication strategies [16]. This benefits situational awareness and facilitates endeavors like self-driving capability, intelligent surveillance, and ecological observation.

Future communication systems have huge potential that will only be achieved through the successful integration of AI with current wireless paradigms. AI not only improves the speed and flexibility of these technologies, but it also resolves their inherent problems, leading to intelligent, sustainable, and ubiquitous wireless connectivity.

6. Challenges

AI provides transformative capabilities to optimize and automate advanced wireless networks, but integrating AI into 5G and B5G ecosystems poses a broad spectrum of technical, operational, and ethical hurdles. These challenges can be associated with the peculiarities of wireless communication environments (high mobility, topology dynamism, resource constraints, and heterogeneous service requirements) and difficulties related to the topic of AI

models. Addressing these issues is essential to ensure that AI-based solutions are scalable, reliable, and applicable to practical implementation.

Availability and Quality of Data: AI models are data-driven and require tremendous amounts of high-quality representative data for training and generating results. In wireless networks, the comprehensive collection of such datasets remains a significant issue, given the requirements of privacy, limited storage capacity, and heterogeneity in the data. Network data is often noisy, incomplete, and/or imbalanced, leading to poor model performance. Furthermore, the specific environment or use case, such as rural settings or emergencies, might not provide sufficient historical data, which constrains the use of supervised learning methods.

Low Latency Requirements and Real-Time Processing Requirements: A large number of 5G and B5G use cases, such as autonomous driving and remote surgery, require URLLC. Nevertheless, classical AI models, especially deep learning models, are computationally demanding and can become a source of delays due to processing and inference times. To achieve edge latency, models must be lightweight, and hardware accelerators must be efficient, which is not always possible or affordable.

Robustness and Model Generalization: AI models that have been trained using controlled settings might not perform as well as expected since networks are highly variable in real-life conditions, including network states, user behavior, and much more. The problem of ensuring that AI solutions can generalize in different circumstances and cope with various unexpected situations, including equipment breakdowns or hacker attacks, has not been solved. Additionally, AI models are vulnerable to adversarial inputs or data poisoning; this threat means that incorrect inputs may deceive these models and pose a serious security risk.

Interoperability and Standardization: The development of wireless systems with AI incorporation necessitates the synchronization of different hardware devices, software architectures, and communication protocols. Nevertheless, there is no provision for unified interfaces and deployment objectives, thereby limiting interoperability and mass usage. Non-standard implementation principles may differ among vendors, resulting in fragmented solutions that are difficult to integrate or scale across varied network infrastructures.

Security Preferences and Privacy: The application of AI in wireless networks commonly implies collecting and processing user information and, therefore, goes hand in hand with issues regarding privacy and data security. The techniques of federated learning and differential

privacy achieve certain solutions at the cost of model accuracy and overhead computation costs. In addition, the AI systems themselves may become targets of attacks (model inversion, inference attacks, and the like) and reveal sensitive information.

Explainability and Trustworthiness: Most AI systems, especially DNNs, will be black boxes, and thus, the rationale behind them will not easily be comprehended. Transparency is a factor of concern that may lower the level of trust and prevent regulatory compliance in mission-critical applications (e.g., healthcare or industrial automation). The essential need in building confidence in the use of AI systems in wireless tasks is to develop explainable AI (XAI) methods that will enable a human user to gain a human-interpretable understanding of model behavior.

Although the power of AI may revolutionize the new generation of wireless systems, these issues will be resolved through interdisciplinary research, workshops on standardization, and the development of strong, transparent, and evolving AI platforms that will reach out to communication systems.

7. Future Directions

AI joins the capabilities of advanced wireless networks and has the potential to define the new generation of communication networks. Future studies are required to progress to the next stage of 5G and B5G, creating more adaptive, efficient, and trustworthy AI as the wireless world becomes even more complicated and dynamic. A potential advancement direction is making AI workloads lighter and more energy-efficient so that they can be implemented on edge devices and embedded systems with low-computing facilities. This is essential for accommodating low-latency applications like autonomous vehicles, smart factories, and telemedicine. It is also possible to investigate neuromorphic computing and spiking neural networks to replicate biological processing and lower power consumption. Federated and decentralized learning is another promising area that enables collaborative model training without global aggregation of data, thus ensuring privacy and fostering distributed intelligence in a network. Combined with approaches such as privacy-preserving techniques (differential privacy, homomorphic encryption), these will provide more secure handling of data in AI-based wireless networks. In addition, XAI will grow even more significant, particularly in safety-critical and regulated areas. Developing models that are interpretable and capable of producing justifiable decisions will help to build more trust and transparency. Lastly,

combining AI with cross-disciplinary technologies like quantum communication, blockchain, and integrated sensing will characterize the future of intelligent, resilient, and autonomous wireless networks.

8. Conclusion

AI can be seen as a basic enabler when it comes to the development of wireless communication systems, especially regarding 5G and B5G networks. Improving the versatility and responsivity of next-generation wireless infrastructures, AI contributes greatly to providing fully or partly automated data-based solutions to challenging tasks processor assignments, mobility planning, network optimization, security augmentation, etc. In this review, the basic AI methods have been presented, along with their significant applications, integration points with emerging wireless paradigms, and the issues experienced in real world implementation. The convergence of AI with the latest communication technologies will be very relevant in attaining fully autonomous, extensible, and stable network ecosystems, as wireless networks become more and more heterogeneous and service-intensive. To reap all the benefits of AI-enabled wireless connections in 6G and beyond, further research and development are paramount to address the current constraints and tap the potential of the novel technology.

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