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Integrating AI into Key Enabling Technologies for 6G Networks: A Review from SDN to Quantum Computing

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ABSTRACT

This review article provides an in-depth analysis of integrating artificial intelligence (AI) into key enabling technologies for sixth-generation (6G) wireless networks. It examines how AI can enhance the performance and efficiency of technologies such as software-defined networking (SDN), network functions virtualization (NFV), network slicing, edge and cloud computing, and quantum communications. The study also covers other emerging technologies like reconfigurable intelligent surfaces, terahertz communications, holography, and neuromorphic computing. It identifies technical, security, and interoperability challenges related to this integration while exploring future perspectives and promising research directions. The article aims to provide a comprehensive understanding of the current state of AI integration in 6G technologies, thereby offering valuable guidance for researchers, engineers, and decision-makers in this rapidly evolving field.

KEYWORDS

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Artificial intelligence
SDN
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Network slicing
Edge and cloud computing
Quantum communications

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1 Introduction

Wireless communication technologies are progressing at a very high rate and due to their progress we are now on the lookout for the Sixth Generation (6G) of mobile networks that will transform connectivity and digital services [1] as shown in Fig. 1. Currently, the roll-out of 5G networks is going on; on the other hand, massive efforts have been towards the development of 6G to fulfill the demands of capacity, latency, reliability, and energy efficiency in future mobile networks [2], [3].

These hyper-connected societies are planned for 6G networks as they are expected to provide support to such applications as the Internet of Senses (IoS), extended reality (ExR), immersive communications like the holo-metaverse communications, and ambient Intelligence [4]. It is predicted that these networks will provide terabit-per-second data rates, sub-millisecond latency, and substantial connection density; however, they have to cover the whole world and consume minimal energy [5].

In order to reach these high objectives, 6G networks will be based on several main technological drivers, including SDN, NFV, network slicing and other enabling technologies [6]. Together with AI, these technologies will form the foundation of future 6G networks.

Artificial Intelligence (AI), broadly defined as the simulation of human intelligence processes by machines, especially computer systems, is set to play a crucial role in 6G networks. It is viewed as one of the key and revolutionary components of 6G networks, expected to strongly enhance various aspects such as performance, efficiency, and flexibility when integrated into enabling technologies. AI can contribute to numerous facets of 6G networks, including dynamic resource management, failure prediction, network data security and privacy, task automation, and real-time response to network conditions.

In SDN, AI can help ensure better management of traffic by the central SDN controller for all subscribers. In the case of NFV, the use of AI can assist in the efficient placement and management of VNFs and their associated resources. With network slicing, AI may play an important role in the intelligent allocation of resources, as well as in automating the management of network slices.

AI will become the key to the optimization of the usage of resources in Edge Computing and Cloud Computing and real-time decision-making. In quantum communications, areas of application of AI include the improvement of the communication protocols as well as the identification of the quantum errors.

In this review, we discuss the integration of AI into key technologies for 6G networks, including SDN, NFV, network slicing, edge and cloud computing, quantum communications, RIS, THz communications, holography, and neuromorphic computing, and we also address the challenges and research perspectives associated with this integration.

To our knowledge, no prior review has comprehensively examined this intersection with all these technologies. The analysis synthesizes recent literature, providing insights into AI's role in enhancing these key technologies. By exploring potential interactions, technical difficulties, security concerns, and research avenues, this review aims to serve as a foundational reference for future research in this rapidly developing field.

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This paper is organized as follows: Section 2 reviews some papers related to AI integration into 6G Key Enabling Technologies. The third section provides an overview of key enabling technologies for 6G. The fourth section offers an in-depth analysis of AI integration into various specific technologies such as SDN, NFV, Network Slicing, Edge and Cloud Computing, quantum communications, and many other enabling technologies, as well as their synergies with AI. The fifth section presents the challenges of integrating AI into 6G technologies, as well as future perspectives and research directions. Finally, in the sixth section, a conclusion for this work is presented.

Fig.1. Emerging applications of next-generation wireless 6G network [3].

2 Related works

This section provides an overview of some papers that address the integration of AI in one or more of the key technologies for 6G.

The integration of AI into Software-Defined Networking (SDN) and Network Function Virtualization (NFV) has been extensively studied for its capabilities to enhance network security and efficiency. Siriwardhana et al. highlighted the potential of AI to strengthen 6G network protection mechanisms by integrating threat detection and predictive analysis techniques into SDN and NFV architectures [7]. Francesco Chiti et al. proposed several heuristics with increasing computational complexity to optimize multi-beam routing strategies focused on Physical Layer Security (PLS) using Reconfigurable Intelligent Surfaces (RIS) in 6G networks. They demonstrated through simulation results the improvement in secrecy rate performance with an increasing number of eavesdroppers and considered user mobility in a pedestrian scenario, showcasing the potential of integrating RIS with Software-Defined Networking (SDN) for enhancing communication security in future wireless systems [8]. Additionally, Akyildiz et al. discussed the fundamental concepts of wireless SDN and NFV, laying the groundwork for future innovations beyond 5G [9]. Du et al. explored the use of machine learning techniques to improve bandwidth, massive access, and ultra-low latency in 6G networks [10], which is relevant for security enhancements based on SDN/NFV. AI plays a crucial role in network Slicing, Zhang et al. discussed the integration of artificial intelligence (AI) in slice networking for 6G, emphasizing its role in enhancing intelligent network management and supporting emerging AI services through a novel AI-native network slicing architecture [6]. Edge Computing and Cloud Computing greatly benefit from AI integration,Yang, H. et al. highlight that integrating AI into edge and cloud computing within 6G networks enhances real-time data processing, reduces latency, and improves overall network efficiency and intelligence by enabling smarter resource management and decision-making at the network edge [11]. Chkirbene et al. introduced a dynamic intrusion detection and classification system using feature selection, highlighting advanced threat detection approaches applicable to SDN/NFV [12]. According to Wallnöfer et al., machine learning can be used to identify and optimize key quantum protocols for long-distance quantum communication, including teleportation, entanglement purification, and quantum repeaters. Their research demonstrates that machine learning approaches can not only reproduce known protocols but also find improved solutions, particularly for asymmetric scenarios with non-uniform channel noise and segment distances. This work paves the way for using machine learning in the design and implementation of quantum networks, which could be crucial for enhancing the security and efficiency of future communication systems, including 6G networks [13]. F. Chiti et al. discuss how Reconfigurable Intelligent Surfaces (RIS) are a key technology for 6G networks, allowing for optimized wave propagation and improved energy efficiency. They highlight that AI can be used to dynamically adjust the properties of RIS to maximize network performance [8]. Terahertz (THz) communications offer extremely wide bandwidths to support ultra-high data rates in 6G networks. AI plays a crucial role in accurately modeling THz channels and optimizing beamforming techniques to overcome high attenuation and signal directivity. Rappaport et al. highlighted the opportunities and challenges of communications beyond 100 GHz, emphasizing the importance of AI in fully exploiting this spectrum [14]. Holography is envisioned as a key technology for immersive communications and extended reality in 6G networks. AI is essential for generating high-quality holograms in real-time and efficiently compressing holographic data. Shi et al. demonstrated how deep neural networks can be used to create photorealistic holograms in real-time, paving the way for new applications in telepresence and mixed reality [15].Neuromorphic computing, inspired by the functioning of the human brain, offers a low-power, highly parallel information processing paradigm, particularly suited to the constraints of 6G networks. M. Davies et al. present a comprehensive review of the results obtained with Intel's neuromorphic processor Loihi across various algorithmic domains, demonstrating its advantages in energy efficiency and performance for specific tasks, particularly with brain-inspired approaches [16].

In this review, we will examine the integration of AI into all these key technologies for 6G networks and discuss the advantages and research perspectives associated with this integration, which have not been previously explored in conjunction with these technologies.

3 An overview of key enabling technologies for 6G

The conceptual foundation of 6G networks can be traced back to the next-generation networks theory proposed by researchers such as Akyildiz et al.in [9] . This framework posits that these networks must be designed to address unprecedented demands in terms of capacity, latency, reliability, and spectral efficiency. It also outlines a specific approach to achieving these goals, involving the use of such technologies as AI, and here is an overview of the different enabling technologies for 6G:

SDN was presented by McKeown et al. and involves the separation of the control plane from the data plane in the network [17]. This separation makes network management more flexible and programmable compared to traditional consolidated networks. The use of AI in SDN leverages this paradigm to enhance the decision-making process and network configuration, enabling more dynamic and efficient management.

The NFV theory that has been created by ETSI [18] aims to virtualize the functions in the network that have always been performed by special equipment. This seems more flexible and quite scalable as well.

Network slicing is a concept introduced by 3GPP whereby several slices are established on a common physical framework [19], [20].

According to Shi et al. Edge Computing is steeped in the principle of localizing processing activities closer to the sources or the end users [21].

The concept of quantum communication was originated by Bennett and Brassard, this theory guarantees the security of communication theoretically [22].

Reconfigurable Intelligent Surfaces (RIS) are surfaces that are artificially created, that can control electromagnetic waves according to a specified program. Di Renzo et al.in [23], have found out that through the help of RIS, the coverage, capacity, and energy efficiency of the wireless network could be enhanced.

The THz communications theory introduced by Akyildiz et al. in [24], presented the usage of extremely high frequencies to establish high data rates.

Holography is a technique of image formation through the interference of light waves to create three-dimensional structures perceived as realistic images. The holography technique was discovered in 1948 by Dennis Gabor, a Hungarian scientist [25], and is expected to be one of the revolutionary applications for 6G networks [26].

Neuromorphic computing being energy efficient shall help bring artificial general intelligence in the post-Moore world. Current approaches have some shortcomings; however, the reconfigurable neuromorphic computing derived from the brain's programmability brings about an efficient resource utilization for the execution of intricate operations [27]. It is believed that it may serve as a highly prospective development for enhancing the energy efficiency and effectiveness of the AI circuits in the 6G networks.

4 Integration of AI into the varios key enabling technologies of 6G

The sixth-generation mobile networks are envisioned as incorporating AI and machine learning (ML) capabilities, paving the way for seventh-generation networks. These advancements will enable more precise and proactive control over resource distribution within the network, facilitate instantaneous enhancements in network performance, and allow for rapid adjustments to operating conditions. Letaief et al.in [2] also have predicted that the AI aspect will be compelled into the 6G construction natively to demand self- optimizing and self-healing networks. Fig. 2 presents AI along with some enabling technologies in the 6G network environment.

4.1 Integration of AI in Software-Defined Networking

In 6G networks, Software-Defined Networking (SDN) plays a significant role since it enables flexibility and programming of the network. The utilization of AI in SDN can help enhance the features and operations of 6G networks tremendously.

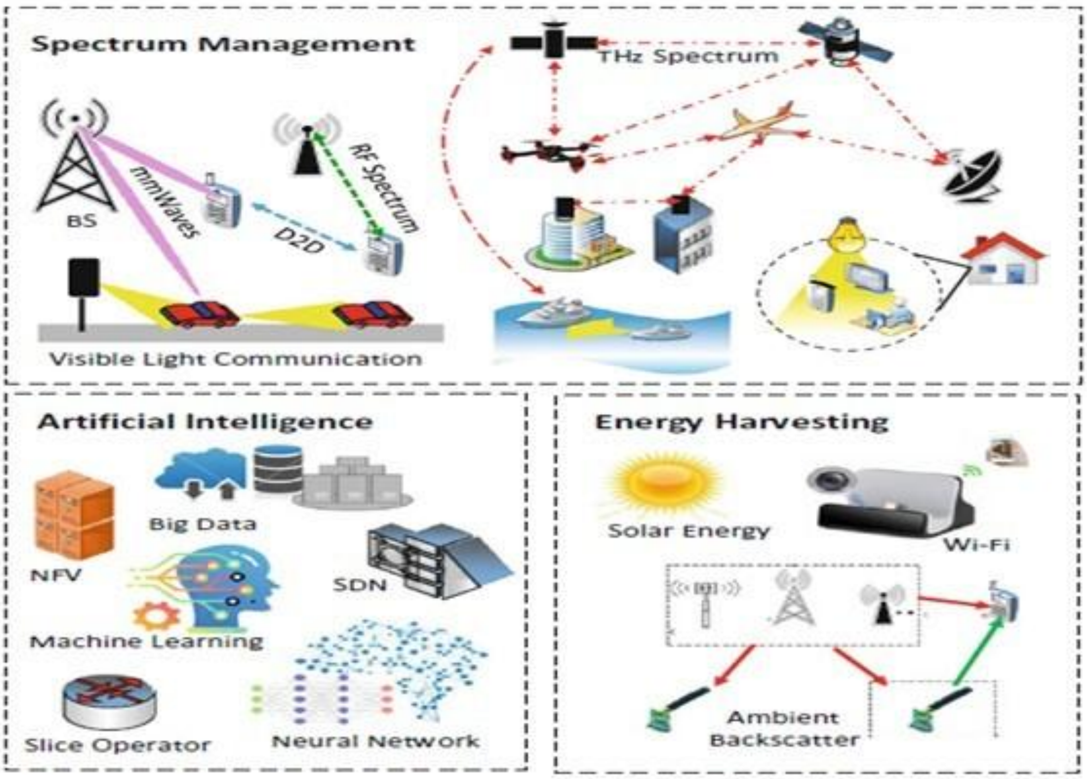

Fig.2. AI and some enabling technologies of 6G Wireless networks [3].

4.1.1 Principles of SDN :

SDN is based on three fundamental principles: These are the principles such as separating the control plane and the data plane, implementing the logical centralization of control, and network programmability [28]. For example the SDN controllers can control network slicing in a centralized fashion [29]. This architecture provides an efficient and more flexible approach of thus managing the available network resources which is vital as implies 6G networks in terms of capacity, latency and reliability.

The network becomes logically centralized in the controller in an SDN network meaning that the controller contains the control logic and has a global view of the network.

This centralization helps in the management and manipulation of resources and quick response to any shift in the network salient features [30]. Today, network programmability enables to dynamically build and change network characteristics through programming interfaces – APIs, which was impossible before [31].

4.1.2 AI Applications in SDN for 6G :

The integration of AI into SDN opens new perspectives for 6G networks:

4.1.2.1 Routing optimization

Some algorithms used in reinforcement learning can also solve the routing problem in real time, as they adapt to existing network conditions and ensure low delays [32] .

4.1.2.2 Predictive traffic management

It is possible to predict traffic congestion and, based on that, modify the network settings using deep learning models for predicting the traffic peaks.

4.1.2.3 Anomaly detection and mitigation

Since unsupervised learning techniques do not require any training data or a reference model, the detection process becomes faster for identifying any suspicious activity in the network, allowing for timely actions to counter security threats.

4.1.2.4 Dynamic resource allocation

Other capabilities include the ability to manage network resources depending on the forecasted traffic to ensure that both the network and services deliver optimum value.

4.1.2.5 Self-configuration and self-optimization

By applying machine learning approaches to SDN networks, they become self-configuring and self-optimizing, freeing them from most interventions.

4.1.2.6 Intelligent network slicing

The usage of AI ensures adaptability in the formation and orchestration of network slices, which are tailored for specific 6G applications.

4.2 AI and Network Function Virtualization

Network Function Virtualization (NFV) is crucial for 6G networks, offering enhanced flexibility and efficiency in resource management. AI integration in NFV promises further optimization, enabling dynamic orchestration, predictive allocation, and automated scaling. This NFV-AI synergy is key to achieving the ultra-low latency, high reliability, and massive connectivity required for advanced 6G applications.

4.2.1 Basic Concepts of NFV :

NFV is an architectural paradigm that aims to virtualize network functions traditionally implemented in proprietary hardware. According to ETSI (European Telecommunications Standards Institute), NFV enables the implementation of network functions in software that can run on a range of industry-standard server hardware, and that can be moved to, or instantiated in, various locations in the network as required, without the need to install new equipment [33], [34].

4.2.2 The key components of the NFV architecture :

1) Virtualized Network Functions (VNFs): software applications that provide specific network functions.
2) NFV Infrastructure (NFVI): the virtualized environment on which VNFs run.
3) NFV Management and Orchestration (MANO): responsible for the lifecycle management of VNFs and orchestration of NFVI resources.

NFV offers several advantages, including reduced equipment and operational costs, greater flexibility in service deployment, and improved scalability [34].

4.2.3 Role of AI in NFV Optimization for 6G :

The integration of AI into NFV for 6G networks aims to improve the efficiency, adaptability, and overall performance of the system. Here are some key areas where AI can optimize NFV:

4.2.3.1 Dynamic VNF orchestration and placement

AI can optimize VNF placement in real-time based on various parameters such as network load, latency, and energy consumption. Reinforcement learning algorithms have shown promising results in this area [35].

4.2.3.2 Proactive resource prediction and management

Machine learning models can predict resource needs and dynamically adjust NFV resource allocation, thereby improving overall system utilization [36].

4.2.3.3 Automatic anomaly detection and resolution

AI can quickly identify anomalies in VNF operation and automatically propose or implement solutions, thus reducing downtime and improving network reliability [37].

4.2.3.4 Energy consumption optimization

AI algorithms can be used to optimize the energy consumption of NFV infrastructures, a crucial aspect for green 6G networks.

4.2.3.5 Enhanced security

AI can improve the security of NFV environments by detecting and mitigating security threats in real-time.

4.3 AI-assisted Network Slicing

Network Slicing is a key technology for 6G networks, enabling the creation of customized virtual networks on a common physical infrastructure. The integration of artificial intelligence (AI) into Network Slicing promises to significantly improve the efficiency, flexibility, and performance of 6G networks.

4.3.1 Fundamentals of Network Slicing :

Network Slicing is a concept that allows dividing a single physical network infrastructure into multiple virtual networks, each optimized for specific service requirements. This approach offers increased flexibility and efficiency in network resource management, allowing operators to meet the varied needs of different 6G use cases [29]. The fundamental principles of Network Slicing include:

4.3.1.1 Isolation

Each network slice operates independently, without interference from other slices.

4.3.1.2 Customization

Slices can be configured to meet specific requirements in terms of latency, bandwidth, reliability, and security.

4.3.1.3 Flexibility

Slices can be dynamically created, modified, and deleted as needed.

4.3.1.4 Resource management

Efficient allocation and optimization of network resources among different slices [38].

4.3.2 AI Contributions to Network Slicing in 6G :

The integration of AI into Network Slicing for 6G networks brings several significant advantages:

4.3.2.1 Dynamic resource optimization

AI can analyze traffic patterns and service requirements in real-time to optimize resource allocation among network slices. Reinforcement learning algorithms have shown promising results in dynamically optimizing resource allocation for Network Slicing [39].

4.3.2.2 Prediction and anticipation of needs

AI models can predict future traffic demands and resource needs, enabling proactive management of network slices. Deep learning techniques have been used to accurately predict resource needs of network slices, thus improving overall system efficiency [40].

4.3.2.3 Automation of slice creation and management

AI can automate the process of creating, configuring, and managing network slices, thereby reducing operational complexity. Machine learning-based approaches have been proposed to automate the configuration and orchestration of network slices [41].

4.3.2.4 Quality of Service (QoS) improvement

AI can continuously monitor slices performance and dynamically adjust their parameters to maintain the required QoS. Deep reinforcement learning algorithms have been developed to optimize QoS in sliced networks, demonstrating significant improvements over traditional approaches.

4.3.2.5 Security and anomaly detection

AI techniques can be used to detect security threats and behavioral anomalies in network slices, thus improving the overall robustness of the system. Unsupervised learning models have been successfully applied to detect intrusions and anomalies in sliced networks.

4.4 AI-enhanced Edge Computing and Cloud Computing

Edge Computing and Cloud Computing are two complementary paradigms that play a crucial role in the architecture of 6G networks.

4.4.1 Principles of Edge and Cloud Computing :

Cloud Computing offers centralized computing and storage resources, while Edge Computing brings these resources closer to users and devices [2]. Cloud Computing relies on centralized data centers that provide on-demand services via the Internet. It offers high computing and storage capacity, significant flexibility, and scalability [6].However, it can suffer from high latency and bandwidth issues for certain real-time applications.Edge Computing, on the other hand, moves data processing and storage closer to the source, at the "edge" of the network. This allows for reduced latency, bandwidth savings, and improved data privacy [1]. Edge Computing is particularly important for 6G applications that require real-time processing, such as augmented reality or autonomous vehicles.

4.4.2 AI Integration into Edge and Cloud Computing for 6G Networks :

The integration of AI into Edge and Cloud Computing for 6G networks offers numerous possibilities for optimization and performance enhancement [4]:

4.4.2.1 Intelligent resource orchestration

AI can dynamically optimize resource allocation between the cloud and the edge based on real-time needs, thereby improving overall network efficiency [42].

4.4.2.2 Workload prediction

Machine learning algorithms can predict demand peaks and proactively adjust resources, thus reducing latency and improving user experience.

4.4.2.3 Enhanced security

AI can detect anomalies and security threats in real-time, both at the edge and in the cloud, thereby strengthening the overall security of the 6G network.

4.4.2.4 Energy consumption optimization

AI techniques can optimize the energy consumption of edge and cloud servers, contributing to the energy efficiency of 6G networks.

4.4.2.5 Quality of Service (QoS) improvement

AI can analyze network conditions in real-time and dynamically adjust parameters to maintain optimal QoS.

4.4.2.6 Predictive maintenance

Machine learning algorithms can predict potential failures of edge and cloud equipment, enabling proactive maintenance and reducing downtime.

4.5 AI in Quantum Communications

Quantum communications represent an emerging field that exploits the principles of quantum mechanics to transmit and process information. Unlike classical communications, quantum communications use quantum states, such as entangled photons, to encode and transmit information [43]. This approach offers unique advantages in terms of security and information processing capacity.

4.5.1 The main concepts of quantum communications :

The main concepts of quantum communications are:

4.5.1.1 Quantum superposition

A qubit can exist simultaneously in multiple states, unlike classical bits.

4.5.1.2 Quantum entanglement

Particles can be linked in such a way that the state of one instantly affects the state of the other, regardless of distance.

4.5.1.3 No-cloning theorem

It is impossible to perfectly copy an unknown quantum state, which enhances communication security [44].

In the context of 6G networks, quantum communications promise to bring significant improvements in terms of security, capacity, and information processing speed [45] .

4.5.2 Applications of AI in Quantum Communications for 6G :

Quantum Communications is anticipated to change the landscape of wireless resource optimization issues in 6G communication systems by improving their security, efficiency, and intelligence. It is regarded as an essential technology that facilitates these advancements.

The integration of AI into quantum communications for 6G opens new perspectives for optimizing and improving these complex systems. Here are some key applications:

4.5.2.1 Optimization of quantum protocols

AI can be used to optimize quantum communication protocols, dynamically adjusting parameters to maximize transmission efficiency and reliability [13]. For example, reinforcement learning algorithms can be employed to adapt quantum key distribution protocols to changing conditions of the communication channel.

4.5.2.2 Quantum error detection and correction

Quantum systems are particularly sensitive to environmental disturbances. AI can play a crucial role in real-time detection and correction of quantum errors [46]. Deep neural networks can be trained to recognize error patterns and apply appropriate corrections, thus improving the reliability of quantum communications.

4.5.2.3 Quantum network management

In the context of 6G networks, AI can be used to efficiently manage quantum network resources, optimizing qubit routing and dynamically allocating quantum resources based on demand.

4.5.2.4 Enhancement of quantum security

AI can strengthen the security of quantum communications by detecting interception attempts and adapting security protocols accordingly. Machine learning algorithms can be used to analyze traffic patterns and identify potential anomalies.

4.5.2.5 Quantum signal processing

AI can be applied to improve quantum signal processing, optimizing the detection and reconstruction of transmitted quantum states. This can lead to better transmission quality and more efficient use of quantum bandwidth.

4.6 AI in Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) represents a promising technology for improving coverage and spectral efficiency in 6G networks. RIS are artificial surfaces capable of manipulating electromagnetic waves in a programmable manner, thus offering unprecedented control over the propagation environment [47].

4.6.1 The integration of AI into RIS :

The integration of AI into RIS can bring several advantages:

4.6.1.1 Dynamic RIS configuration

AI can be used to adjust RIS configuration in real-time based on propagation conditions and user needs, thus maximizing network performance [47].

4.6.1.2 Channel prediction

Machine learning algorithms can predict propagation channel characteristics, enabling proactive configuration of RIS [48].

4.6.1.3 Intelligent beamforming

AI can optimize beamforming patterns by combining RIS capabilities with smart antennas, thereby improving signal quality and reducing interference [47].

However, integrating AI into RIS also poses challenges, particularly in terms of computational complexity and energy consumption. Further research is needed to develop efficient and low-latency AI algorithms adapted to RIS constraints [47].

4.7 THz Communications

The upcoming 6G cellular technology aims to provide enhanced system capacity, improved performance, and network sensing abilities. The terahertz (THz) band is considered a potential key enabler for 6G due to its large unused frequency spectrum, high spatial resolution resulting from short signal wavelengths, and extensive bandwidth.

4.7.1 The Integration of AI into THz Communications :

AI can play a crucial role in the efficient exploitation of the THz spectrum:

4.7.1.1 Channel modeling

AI can be used to develop accurate THz channel models, taking into account the unique characteristics of propagation at these frequencies [49].

4.7.1.2 Adaptive beamforming

Reinforcement learning algorithms can optimize beamforming techniques for THz communications, compensating for high attenuation and blocking effects [50], [51].

4.7.1.3 Resource allocation

AI can efficiently manage the allocation of THz spectral resources, taking into account channel variability and application requirements [52].

4.7.1.4 Signal detection and estimation

Deep learning techniques can improve signal detection and estimation in THz bands, where distortions and noise are major challenges.

Despite these potential advantages, integrating AI into THz communications still requires significant advancements, particularly in the development of hardware capable of processing THz signals at high speed and with low energy consumption.

Table 1. The integration of AI into key enabling technologies of 6G networks.

Technology	Without AI	With AI	AI Advantages	References
SDN (Software-Defined Networking)	Centralized network management, programmability	Intelligent decision-making, dynamic network optimization	Improved efficiency, real-time adaptation to network conditions	[6], [7], [17], [28], [29], [30], [32]
NFV (Network Function Virtualization)	Virtualization of network functions	Intelligent orchestration of network functions, dynamic placement of network functions	Optimized resource allocation and dynamic orchestration	[6], [7], [9], [18], [33], [34], [35], [36], [37]
Network Slicing	Static resource allocation	Autonomous slice creation and management	Enhanced resource efficiency and service customization	[6], [10], [19], [20], [29], [38], [39], [40], [41]
Edge Computing and Cloud Computing	Decentralized data processing	Real-time decision making and resource optimization	Reduced latency, improved service quality, and efficient resource management	[1], [2], [4], [6], [12], [42]
Quantum Communications	Secure data transmission using quantum states	Optimized protocols and error correction	Enhanced security, reliability, and efficiency of quantum communications	[6], [13], [22], [43] [44], [45], [46], [54]
RIS (Reconfigurable Intelligent Surfaces)	Static manipulation of electromagnetic waves	Dynamic optimization of surface properties	Improved coverage, energy efficiency, and network performance	[8], [23], [47], [48]
THz Communic-ations	High bandwidth with propagation challenges	AI-driven beamforming and channel modeling	Overcoming high path loss, improved data rates, and efficient spectrum use	[14], [24], [49], [50], [51], [52]
Holography	Real-time holographic communications	AI-based data compression and quality optimization	Enhanced transmission quality and efficient bandwidth usage	[15], [25], [26]
Neuromorphic Computing	Energy efficient, brain-inspired computing	Adaptive learning and real-time processing	Improved energy efficiency and cognitive processing capabilities	[16], [27], [53]

4.8 Holography

Holography is envisioned as a revolutionary application for 6G, enabling immersive experiences and ultra-realistic visual communications. AI can significantly contribute to realizing this vision [26].

4.8.1 The Integration of AI into Holography :

The integration of AI into holographic systems holds great promise for enhancing various aspects of holographic communications for 6G.

4.8.1.1 Image compression and processing

Deep learning algorithms can be used to efficiently compress voluminous holographic data and enhance the quality of reconstructed images.

4.8.1.2 Real-time rendering

AI can accelerate real-time hologram rendering, reducing latency and improving user experience.

4.8.1.3 Network adaptation

AI techniques can optimize holographic data transmission based on network conditions, ensuring consistent quality of service.

4.8.1.4 Motion prediction

Machine learning can be used to predict user movements, allowing for pre-rendering of holograms and thus reducing perceived latency.

However, integrating AI into holographic systems poses challenges in terms of required computing power and latency. Further research is needed to develop efficient AI algorithms and hardware architectures adapted to the constraints of holographic communications.

4.9 Neuromorphic Computing

Neuromorphic computing, inspired by the functioning of the human brain, is considered a promising technology for improving energy efficiency and performance of AI systems in 6G networks [53]. Its integration can bring several advantages:

4.9.1 Real-time processing :

Neuromorphic architectures can process data in real-time with low latency, which is crucial for time-sensitive 6G applications.

4.9.2 Energy efficiency :

Neuromorphic computing can significantly reduce the energy consumption of AI systems, thus contributing to the sustainability of 6G networks.

4.9.3 Adaptive learning :

Neuromorphic systems can continuously adapt to the changing network environment, thereby improving robustness and flexibility.

4.9.4 Distributed processing :

Neuromorphic computing can facilitate distributed data processing at the edge device level, reducing the load on the core network.

Despite these potential advantages, integrating neuromorphic computing into 6G networks poses challenges, particularly in terms of technological maturity and compatibility with existing systems. Further research is needed to develop neuromorphic architectures tailored to the specific requirements of 6G networks.

In summary of the above, we present Table 1, which gathers all the key 6G technologies. It details what these technologies offer to the 6G network, both without and with artificial intelligence. Additionally, it highlights the benefits and advantages of integrating artificial intelligence into these technologies.

Table 2. The challenges, future perspectives, and research directions for integrating AI into key 6G technologies.

Technology	Challenges	Future Perspectives and Research Directions	Ref
SDN (Software-Defined Networking)	- Scalability of AI-driven control planes - Real-time decision making in complex networks - Security of centralized control	- fully autonomous systems capable of self- management and security. - Distributed AI for network management - Self-organizing and self-healing networks - AI-driven network slicing optimization	[7] [55] [56] [57]
NFV (Network Function Virtualization)	- Resource allocation optimization - Performance isolation - Dynamic service chaining	- AI-powered automated deployment and scaling - Predictive maintenance of virtual network functions - Energy-efficient NFV orchestration	[7] [9] [56] [57]
Network Slicing	- End-to-end slice management - Multi-tenant resource allocation - QoS guarantee in dynamic environments	- AI-driven autonomous slice creation and management - Cross-domain slice optimization - Adaptive slice reconfiguration based on real-time demands	[10] [40] [56] [58]
Edge and Cloud Computing	- Latency-sensitive task offloading - Energy efficiency in distributed computing - Privacy preservation in edge AI	- Federated learning for distributed edge intelligence - AI-driven workload balancing between edge and cloud - Secure and privacy-preserving edge AI frameworks	[11] [58] [59]
Quantum Communications	- Integration of classical AI with quantum systems - Quantum error correction - Scalability of quantum networks	-Quantum machine learning for secure communications -AI-assisted quantum key distribution - Hybrid classical-quantum network optimization	[54] [60] [68]
RIS (Reconfigurable Intelligent Surfaces)	- Real-time reconfiguration of large-scale surfaces - Channel estimation and modeling - Energy efficiency of active elements	- AI-driven optimal RIS configuration - Joint optimization of RIS and beamforming - Self-adaptive RIS for dynamic environments	[23] [61]
THz Communications	- Accurate channel modeling at THz frequencies - Beam alignment and tracking - Overcoming high path loss	- AI-powered beamforming and precoding - Intelligent reflective surfaces for THz communications - Machine learning for THz channel estimation and prediction	[14] [62]
Holography	- Real-time processing of massive holographic data - Bandwidth requirements for holographic transmission - Quality of experience in holographic communications	AI-based holographic data compression - Intelligent rendering and transmission of holographic content - Perceptual optimization of holographic displays	[15] [63] [64] [65] [66]
Neuromorphic Computing	- Integration with traditional computing architectures - Energy efficiency at scale - Development of neuromorphic algorithms for 6G applications	- Neuromorphic chips for ultra-low latency edge computing - Bio-inspired learning algorithms for network optimization - Hybrid neuromorphic-quantum systems for 6G	[16] [67] [68] [69]

5 Challenges of AI integration in key 6G technologies : perspectives and research directions

The integration of artificial intelligence (AI) into key enabling technologies of 6G networks presents a series of complex and multidimensional challenges. Among these challenges are the management of data security and privacy, optimization of energy efficiency, and the need to develop AI algorithms capable of operating in real-time in highly dynamic environments. Moreover, interoperability between different technologies and standardization of protocols remain major obstacles. However, future perspectives and research directions are promising. Advances in machine learning, neural networks, and massive data processing are paving the way for innovations that could radically transform the connectivity and capabilities of 6G networks.

Table 2 details these challenges and perspectives, offering a clear overview of the areas requiring particular attention to successfully integrate AI into key enabling 6G technologies.

6 Conclusion

This review has thoroughly examined the integration of artificial intelligence (AI) into key enabling technologies of 6G networks, offering a comprehensive perspective on the current state of research and future directions.

AI plays a crucial role in the development and optimization of 6G networks, underpinning the entire architecture from network management to service provision. Its integration into Software-Defined Networking (SDN) and Network Function Virtualization (NFV) enhances capabilities, enabling intelligent decision-making, dynamic network management, and optimization of virtualized network functions.AI also improves resource allocation and autonomous management in Network Slicing, and enhances Edge and Cloud Computing by enabling efficient resource management and real-time decision-making. RIS combined with AI can revolutionize 6G network capabilities by improving coverage and reliability.

The review explored AI's potential in quantum communications and its synergy with technologies like Reconfigurable Intelligent Surfaces (RIS), Terahertz (THz) communications, and holography. However, challenges such as system complexity, security and privacy concerns, energy consumption, and interoperability issues must be addressed. The potential impact of AI on 6G networks is significant, leading to autonomous networks with advanced service personalization, improved energy efficiency, and enhanced security.AI could facilitate unprecedented convergence between technologies, creating a ubiquitous communication ecosystem and enabling revolutionary applications like extended reality and holographic communications.

Ultimately, integrating AI into 6G technologies represents a significant advancement in communication systems, promising improved performance and efficiency. Addressing the identified challenges and exploring synergies between AI and emerging technologies is crucial for realizing this potential. The advent of AI-assisted 6G networks marks a revolution in communications, with profound implications for various sectors and new opportunities for innovation and human progress.

Declaration of Competing Interest

The authors declare no competing interests.

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