

# Artificial intelligence and machine learning in 6G wireless communication networks

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## Abstract

The high-paced development of wireless communication technologies brought about the growing need of smart, autonomous, and ultra-high-performance network structures, and the combination of Artificial Intelligence and Machine Learning in the 6G wireless communication networks is a major research issue. The conventional network management techniques cannot support the new demands that include ultra-low latency communications, intelligent spectrum management, mass connectivity, and real-time dynamic resource provision. This paper is a systematically-conducted literature review on the recent research on AI-driven networks, edge AI, federated learning, intelligent radio access network design, and AI-native architecture in next-generation networks based on PRISMA. The review focuses on the possibilities of self-organizing networks, digital twin networks, and smart connectivity that machine learning, deep learning, and autonomous wireless systems provide to the next generation of wireless networks working in terahertz communication ranges and integrated sensing and communication landscape. The findings indicate that AI based resource allocation, intelligent surfaces of reconfigurability, massive mimo optimization and network automation are all effective towards improving spectral efficiency, reliability and energy efficiency of 6G wireless communication. Moreover, the paper has also noted the increased importance of smart security mechanisms, distributed learning, and edge computing in enabling scalable and secure AI-native architectures. The results also indicate that the next generation wireless networks will be based upon intelligent spectrum management, autonomous control, and real-time data analytics to accommodate the new applications in holographic communication, smart cities, extended reality, and connected autonomous systems.

Keywords: Big data analytics, Deep learning, 6G communication networks, Artificial intelligence, Wireless systems, Federated learning.

## 1. Introduction

The sixth-generation wireless communication networks have occurred due to the fast development of wireless communication technologies and will provide the not previously achieved connectivity, intelligence, and automation with the introduction of Artificial Intelligence and Machine Learning into the very structure of the networks. In contrast to the earlier generations of mobile communication system, 6G wireless communication is being developed as an AI-native network with intelligent decision-making, autonomous control, and real-time optimization integrated in all communication stack layers [1-2]. The increasing need to have the lowest of the latency in communication, the highest number of devices connected to the network, intelligent control of the spectrum and high-capacity data transmission has rendered the traditional rule-based network management not enough to support the next generation wireless networks. With the increasing pace of digital transformation in industries like smart cities, connected healthcare, extended reality, and autonomous transportation, the necessity of AI-enabled network features of adaptive learning and the use of self-organizing behavior has grown in importance. The technological base of next generation networks is likely to be characterized by

emerging technologies like terahertz communication, ultra-massive MIMO, reconfigurable intelligent surfaces and integrated sensing and communication, and computational needs to control highly complex and dynamic wireless networks are fulfilled by Machine Learning, Deep Learning and distributed intelligence. These advances suggest that the successful implementation of 6G wireless communication networks will require a close connection between the successful incorporation of Artificial Intelligence, edge AI, and federated learning into intelligent radio access network architecture and network automation solutions.

The importance of incorporating the concepts of Artificial Intelligence and Machine Learning into the 6G wireless communication network is that the intelligent system will no longer have the constraints that can be found in the current 5G and beyond-5G architectures especially in scalability, power consumption, dependability, and self-sufficiency. The next generation wireless networks will provide microsecond latency, very rapid data rates, and a continuously connected state of terrestrial, aerial, satellite, and underwater communications, that are highly heterogeneous and cannot be effectively addressed by conventional optimization methods [2]. AI-controlled resource aids and smart spectrum allocation and self-organizing networks can also provide dynamic changes to the evolving network state to enhance spectral performance, power savings, and quality of service. Moreover, the influence of the fast spread of Internet of Things devices, immersive applications and data-intensive services demand an intelligent network automation that becomes able to predict the trend of traffic and congestion, as well as secure the communication process in a real-time environment. Digital twin networks and AI-based network simulation has also become a significant concept in recent studies so that operators can model and optimize complex network communication systems prior to implementation. These tendencies indicate that the transition to AI-native architecture is not a choice but a necessary step towards the performance goals of the future wireless networks and empowering fully autonomous wireless systems that will be able to automatically configure themselves, heal themselves, and optimize themselves.

The current research environment indicates that the field of Machine Learning, Deep Learning, federated learning, and edge AI application in the different aspects of 6G wireless communication, such as intelligent radio access network control, beamforming optimization, channel estimation, network slicing, and security management, has achieved major advancements. Recent research stresses that edge AI and distributed intelligence will be a key factor in the reduction of latency and enhancement of privacy since data processing will be as close to the user as possible instead of fully relying on centralized cloud services [2-4]. Federated learning has become one of the promising solutions to empower the approach of collaborative model training without exchanging sensitive information, which is especially applicable to intelligent wireless systems that work in a large-scale and heterogeneous environment. Moreover, the reconfigurable intelligent surfaces and embedded senses and communications technologies are under discussion as the most important enabling technologies of smart connectivity to enable networks to adapt the signal propagation dynamically and enhance the coverage in difficult environments. There is also increasing attention of digital twin networks as an effective predictive maintenance, network planning, and performance optimization tool, which can be used to monitor complex wireless infrastructures in real-time. Nonetheless, with such evolution, the literature is still disjointed with various technologies being discussed in isolation, thus, it is challenging to come up with a clear picture of how Artificial Intelligence and Machine Learning can be methodically incorporated into 6G wireless communication networks.

Despite the extensive body of research on specific components of AI-driven networks, there are still a number of significant gaps in the research that restrict the usefulness of fully autonomous wireless systems. The high computational complexity of Deep Learning algorithms is one of the biggest challenges and demands efficient hardware acceleration and energy-conscious design that will allow them to be used in real-time in resource-constrained environments [5-6]. The other gap is that there are no standard frameworks of AI-native architecture that makes it hard to interoperate between various components of the network and hinders the creation of scalable solutions. The combination of terahertz communication, non-terrestrial networks, and intelligent spectrum management presents new issues concerning the signal propagation, the mobility management, and the cross-layer optimization that

demand sophisticated approaches in the field of the Machine Learning. The security and privacy issues are also the burning issues because autonomous wireless systems should be capable of identifying attacks, eliminating the leak of data, and making reliable decisions without human interference. Also, the increased adoption of distributed intelligence, blockchain security, and digital twin networks poses new challenges on the computational load, synchronization, and real-time coordination of the large-scale communication infrastructures. Such outstanding concerns demonstrate the necessity of a systematic literature review, which would study the role of Artificial Intelligence and Machine Learning in all levels of 6G wireless communication networks and not in remote technologies.

This study aims to present in-depth literature review of Artificial Intelligence and Machine Learning in 6G wireless communication networks by examining the recent studies on AI-based networks, intelligent radio access networks, edge AI, federated learning, reconfigurable intelligent surfaces, digital twins networks, and autonomous wireless systems. This review seeks to find the significant technological trends, how the current methods are working, and what the challenges to do in the research are in order to have fully intelligent next generation networks [7,8]. The paper also aims at analyzing the role of novel ideas like integrated sensing and communication, ultra-massive MIMO, intelligent spectrum management, and AI-assisted network automation in the creation of intelligent connectivity and high-performance wireless systems. Based on the results of a recent literature analysis, the review also offers a systematic knowledge on how Artificial Intelligence can revolutionize wireless communication between programmable systems to self-learning and self-evolving networks that can address the needs of future digital society.

The primary value of the paper is the creation of a systematic and recent literature review that unifies the recent progress in the field of Artificial Intelligence, Machine Learning, and 6G wireless communication through a systematic review process. This study brings together various research areas such as AI-native networks, distributed intelligence, terahertz communication, intelligent radio access network control, and 6G security as compared to the previous surveys, which are specific to the technologies, to present a holistic picture of the future wireless networks [9-12]. The review reveals developing trends that have a high potential of future citation, unresolved research issues, intelligent automation, edge computing and autonomous wireless systems in determining the next generation networks. This paper focuses on the synthesis of the latest trends and future research focus by offering a foundation on the existing knowledge on Artificial Intelligence and Machine Learning to the 6G wireless communication network, and future research to achieve full-intelligence, adaptive, and self-organizing communications systems.

## **2. Methodology**

To aid in the transparency, reproducibility, and methodological rigor of uncovering and integrating available literature on artificial intelligence and machine learning usage in 6G wireless communication networks, this literature review conformed to the Preferred Reporting Items of PRISMA 2020 guidelines (Fig. 1). Four major peer-reviewed academic databases, including Scopus, Web of Science (WoS), IEEE Xplore, and PubMed, were searched systematically and comprehensively to include published papers and other relevant materials in this field of study within the January 2019 to December 2025 cohort of publications and find the latest developments in the area of research. The Boolean search terms were drawn up with caution to achieve maximum sensitivity and specificity. In the case of Scopus and Web of Science, the following search queries were used: (TITLE-ABS-KEY("6G" OR sixth generation wireless or beyond 5G) AND TITLE-ABS-KEY(artificial intelligence) OR TITLE-ABS-KEY(machine learning) OR TITLE-ABS-KEY(deep learning) OR TITLE-ABS-KEY(neural network) OR TITLE-ABS-KEY(reinforcement learning) OR TITLE-ABS-KEY(federated learning)) AND In the case of IEEE Xplore, the keywords were modified as follows: (6G or sixth generation or B5G) and (wireless networks or cellular networks or network architecture or physical layer or mmWave or terahertz), and PubMed was searched with terms (6G wireless) or (next-generation network).

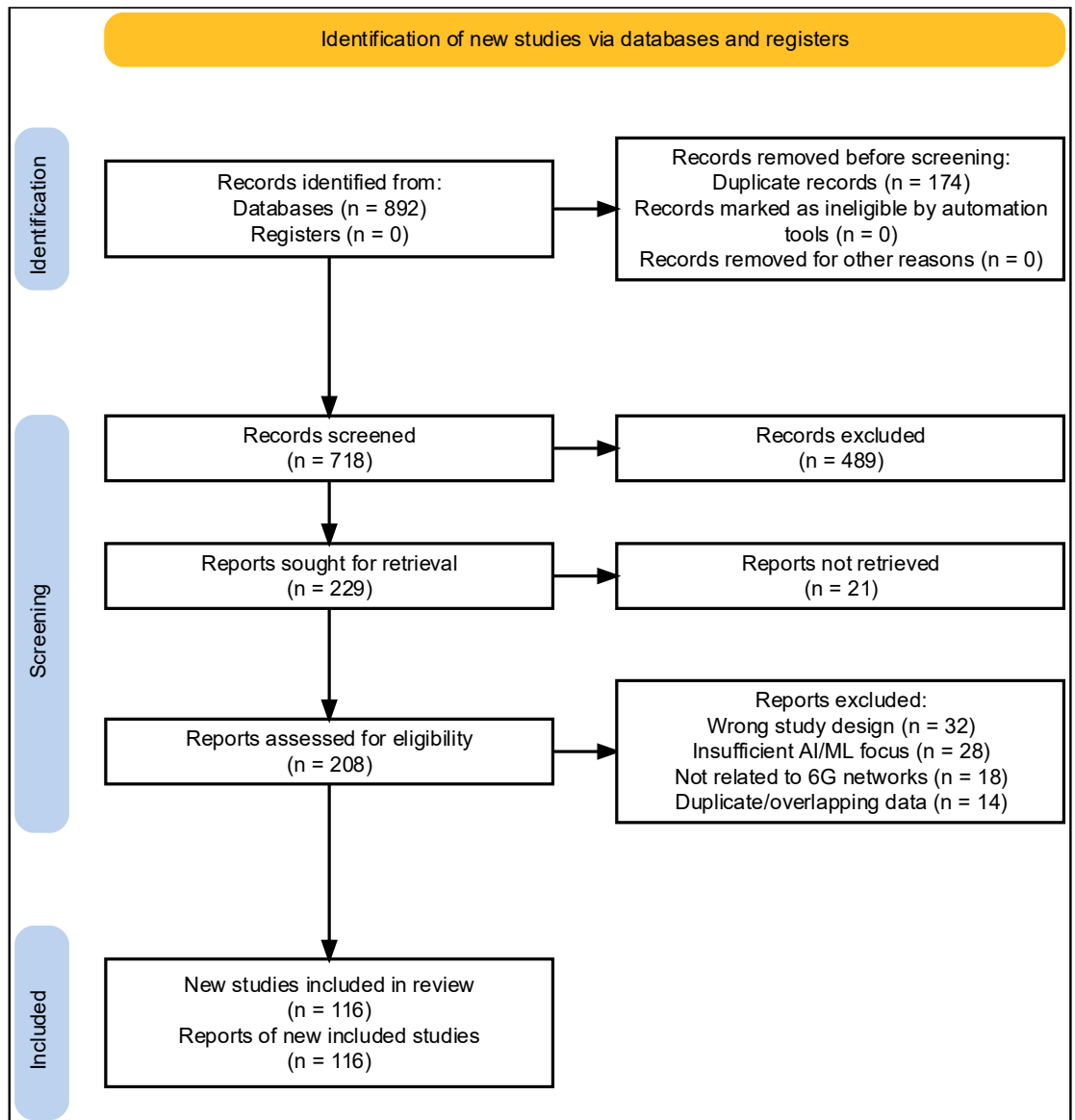


Fig.1 PRISMA Framework

The primary search on the database brought up 892 records. After loading in all outcomes into a reference management tool, 174 duplicate records were found and deleted leaving 718 unique records that were sent to the title and abstract screening phase. All 718 records were screened using predetermined inclusion and exclusion criteria by two reviewers, and 489 records were excluded during the screening phase since they were not relevant to the topic of the research; 229 reports were requested as full-text, and 21 of them were not retrieved because of access controls or unavailability. Two hundred and eight full-text articles were evaluated to be eligible. Inclusion criteria were that the studies: (1) mention AI or ML techniques within 6G or next-generation wireless communication networks; (2) are peer-reviewed journals or conference papers; (3) are in English; and (4) are published between 2019 and 2025. Exclusion criteria removed papers that: (1) discussed 5G or earlier and only had no 6G projections; (2) involved no significant analytical component of a methodology as being purely editorial or opinion; or (3) included overlapping datasets with prior studies that were already included in the analysis. After the complete eligibility of full-text review (n = 92), the reasons of exclusion included: wrong study design (n = 32), insufficient AI/ML emphasis (n = 28), no relevance to 6G network (n = 18), and overlapping data (n = 14) and duplication with other included studies. Finally, the evidence base of this systematic literature review of AI and ML in 6G wireless communication networks was created by including 116 studies that met all inclusion criteria and were included in the final synthesis.

### **3. Results**

#### *3.1 Techniques and Algorithms*

##### **Intelligent 6G Wireless Communication by Deep Learning Techniques**

The deep learning method has become among the most powerful means of realizing Artificial Intelligence in 6G wireless communication networks due to its capability to learn complicated nonlinear interactions in the high-dimensional wireless space. Deep Neural Networks, Convolutional Neural Networks, and Transformer-based networks are gaining traction in the next generation networks as channel estimation, signal detection, beamforming optimization, and intelligent radio access network control [7,13-15]. Compared to traditional mathematical optimization methods, Deep Learning has the ability to approximate the dynamics of a communication environment without an explicit analytic expression, which is required in the case of ultra-dense networks, terahertz communication, and massive MIMO systems. Deep Learning has the capability to handle high amounts of real-time data, and hence is applicable in the context of artificial intelligence networks in which network automation, intelligent spectrum management, and autonomous wireless systems need to run over time, with minimal human operator involvement. Recent trends in research show that edge AI architectures are being coupled with Deep Learning-based algorithms to minimize the latency and provide the capacity to make real time decisions, helping to support ultra-low latency communication and high-reliability services needed in future wireless networks. The growing applications of Deep Learning in semantic communication, digital twins networks, and combined sensing and communications show that it is the core element in changing the conventional communication systems to intelligent and adaptable infrastructures.

##### **Autonomous Network Optimization using Reinforcement Learning**

It is apparent that Reinforcement Learning is an important algorithmic model of autonomous wireless systems in 6G wireless communication networks since it allows intelligent agents to acquire an optimal policy as they interact with dynamic environments. In completely complex next-generation networks, the application of Reinforcement Learning is prevalent in resource allocation, power control, mobility management, and network slicing where decisions need to be made in a continuous fashion with uncertain conditions that need to be optimally made [16]. Deep Reinforcement Learning integrates deep learning networks with the theory of reinforcement learning which enables wireless networks to adjust to dynamic traffic and user mobility, as well as channel conditions, without the use of preset rules. Such approach is especially significant to AI-based networks with operation in heterogeneous environments that comprise terrestrial, aerial, satellite, and non-terrestrial networks. Intelligent spectrum management is also using Reinforcement Learning algorithms to allocate and deallocate frequency bands dynamically to maximize spectral efficiency and minimize interference. Reinforcement Learning coupled with edge AI and distributed intelligence also boosts scalability by enabling autonomous decision-making at various levels of the communication architecture. With wireless networks becoming increasingly complex in the future, Reinforcement learning will be a significant component in the attainment of self-organizing networks and the realization of full self-reliance 6G networks.

##### **Distributed Intelligence Federated Learning in 6G Networks**

As an implementation of distributed Machine Learning, Federated Learning has received much popularity because it allows collaborative training of models without access to underlying data, which is especially applicable to AI-native networks with privacy concerns. This is because in 6G wireless communication, billions of devices on the network edge create data, such as sensors, mobile terminals, and intelligent vehicles, and thus centralized learning is not efficient and secure [9,16-18]. Federated Learning enables the devices to learn local models, and transfer only the model parameters, thus minimizing communication costs and enhancing data privacy. The method is especially applicable to edge AI, smart radio access networks and smart connectivity applications that require real-time processing. Reconfigurable intelligent surfaces are also being integrated with Federated Learning as well as with integrated sensing and communication to facilitate adaptive control of wireless environments. Recent research directions reveal that to enhance scalability and security in large-scale

autonomous wireless systems higher-order variants, like quantum federated learning and hierarchical federated learning, are under investigation. Such advancements demonstrate that Federated Learning will be a basis algorithm in distributed intelligence in the next-generation wireless networks.

#### Network topology optimization on Graph Neural Networks

GNNs have become an influential algorithm method to learn the complex topology of an 6G wireless communication network, where communication networks composed of devices, base stations, and communication links are typically highly connected. Graph Neural Networks are more able to process graph-structured data and learn the best communication strategies, which traditional Machine Learning methods are not always able to capture the relationship between network nodes [2,19-20]. These algorithms are applied to optimize routing, manage interference, as well as allocate resources in ultra-dense networks in next-generation networks. Graph-based learning can be especially useful in systems with massive MIMO, in intelligent radio access networks, where it is necessary to optimize interactions of multiple antennas and users at the same time. The digital twin networks are also using Graph Neural Networks to model the behavior of a network and forecast the network performance in varying conditions. These algorithms are very applicable to AI-based networks where they need to work in a dynamic and heterogeneous environment because of their capacity to generalize to various network configurations. With the shift to 6G wireless communication and distributed intelligence, as well as autonomous operation, the application of Graph Neural Networks should become the indispensable resource to optimize the processes on a large scale and control the network intelligently.

#### Ultra-Low Latency Communication Edge AI Algorithms

Edge AI is an imperative approach to facilitate real-time intelligence in 6G wireless communication networks since it can enable Machine Learning models to be deployed to the data source rather than centralized processes with the cloud. Ultra-low latency communication is a core need in systems where performance deteriorates with minute delays, e.g., autonomous vehicles, extended reality and industrial automation [9,21-23]. Edge AI algorithms minimize the latency by carrying out the inference and learning at the base stations, access points, or at the user equipment, eliminating the necessity of long distance transmissions of the data. The method also enhances privacy and minimizes the connectivity network congestion which is crucial in the massive connectivity case. Federated learning, distributed intelligence, and network automation are often used together with edge AI to develop AI-native scaleable frameworks capable of dealing with billions of connected devices. More recently, it can also be seen that edge AI is being combined with digital twins networks and intelligent spectrum management to provide predictive optimization and adaptive control in future wireless networks. These methods indicate that edge intelligence is one of the fundamental elements of autonomous wireless systems in 6G settings.

#### Algorithms of AI-Controlled Reconfigurable Intelligence Surfaces

Reconfigurable Intelligent Surfaces is a revolutionary technology in 6G wireless communication and Artificial Intelligence algorithms are necessary to control the surfaces in real time. Smart surfaces have the capacity to alter the way electromagnetic waves propagate and networks can do so to better their coverage and reduce interference and spectral efficiency [24-26]. The effective form of surface elements is decided using Machine Learning algorithms depending on the channel conditions, the position of the user, and the low or high traffic demand. Supervised Learning, Reinforcement Learning and Federated Learning have been regularly used to optimize reflection coefficients and beamforming designs in intelligent radio. Reconfigurable intelligent surfaces that are controlled by AIs are especially applicable in terahertz communication and indoors where signal blockage is a significant issue. Combination of smart surfaces with distributed intelligence as well as edge AI facilitates the establishment of adaptive wireless environments which automatically adjust to changing conditions. The techniques will be critical in realizing high capacity and energy efficient next generation networks.

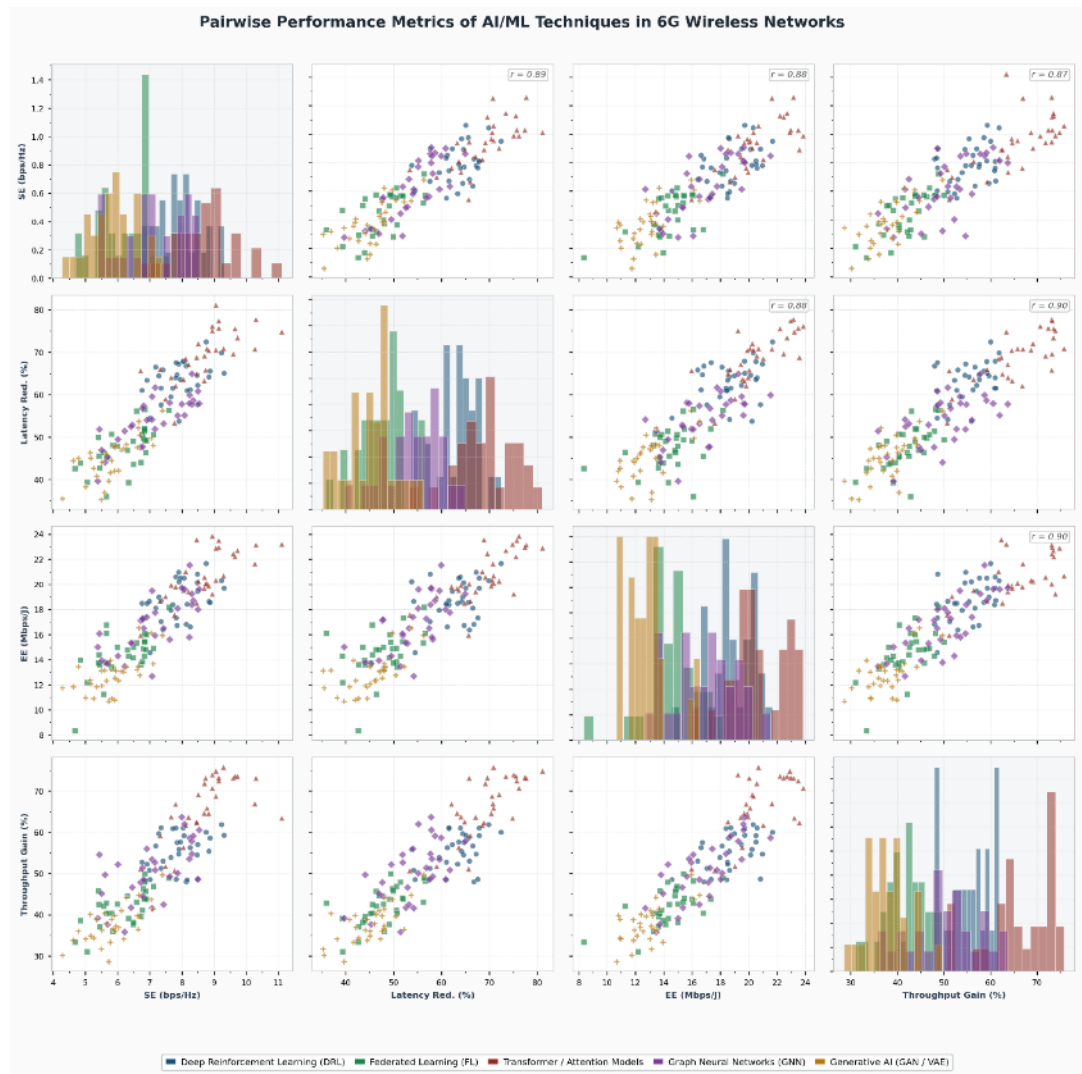


Fig. 2 Pairwise Scatter Matrix of AI/ML Performance Metrics

Fig. 2 is a 4×4 symmetric scatter matrix with Pearson  $r$  annotations and diagonal histograms. Compares four core 6G KPIs, Spectral Efficiency (bps/Hz), Latency Reduction (%), Energy Efficiency (Mbps/J), and Throughput Gain (%), across five ML paradigms. The diagonal reveals each technique's univariate distribution. Strong positive correlations ( $r \approx 0.63\text{--}0.72$ ) are visible across all pairs, confirming that high-performing techniques tend to excel holistically. Transformer/Attention models cluster in the top-right high-performance quadrant, while Generative AI shows the widest spread.

#### Algorithms of Semantic Communication of Data-Efficient Transmission

Semantic communication is a new algorithmic protocol of 6G wireless communication that is aimed at transmitting meaningful information instead of raw data, which enhances efficiency and bandwidth in use. Extracting semantic elements of the signals transmitted by the machines with the help of Machine Learning and Deep Learning models enables networks to restructure the intended message even when some part of it has been lost [8,27-30]. This is especially applicable to applications that require large amounts of data to be communicated in real time with little latency like in the case of extended reality, holographic communication and intelligent sensing. Semantic communication algorithms are typically used with edge AI and distributed intelligence to allow them to process and achieve adaptive compression in real-time. Semantic level-level optimization is also helpful in enhancing energy efficiency and alleviating network congestion that is vital in the case of massive connectivity. With the future development of wireless networks towards intelligent and context-aware communication, semantic communication is predicted to be a methodology of successful and trustworthy data flow in AI-native networks.

### Algorithms of Digital Twin and Predictive Analytics

Digital Twin networks are based on Artificial Intelligence and Machine Learning algorithms to develop virtual representations of physical communication systems with the ability to monitor, predict, and optimize them in real-time. The digital twins, created in 6G wireless communication networks, are utilized to model the behavior of the network, forecast its failures, and optimize the allocation of resources, and the changes are implemented in the actual system before [9,31-33]. Predictive analytics algorithms process large amounts of network data to detect trends and predict the state of the network, and it allows proactive management of the network. Such methods come in handy especially in intelligent radio access networks, network automation, and self-organizing networks, where it is needed to adapt in real-time. Distributed intelligence and scalable optimization are also being combined with digital twin algorithms and edge AI and federated learning. Predictive modeling is likely to be more significant in the future with more sophisticated and autonomous wireless networks.

### Machine Learning and Advanced Optimization Algorithms quantum-based

Quantum Machine Learning is a relatively new field of research that has significant potential to be cited in 6G wireless communication networks in the future and has new ways to address complex optimization problems that classical algorithms have difficulties with. Beamforming, channel estimation, and resource scheduling of a large-scale network can be enhanced by utilizing quantum-inspired optimization methods [34-36]. Such algorithms are also relevant in non-terrestrial networks and terahertz communication where the dimension of optimization is high. Quantum federated learning, quantum-assisted reinforcement learning are under investigation to improve the security, privacy and efficiency of AI-native networks. It can be inferred that the convergence and more precise predictions that are obtained through the combination of quantum algorithms with distributed intelligence and edge computing will be applicable in the future autonomous wireless system. With the ongoing development of research in the fields of quantum communication and AI, these methods will probably become a significant part of the further-generation network optimization.

### An example of integrated Sensing and Communication Algorithms in 6G Systems

The important characteristic of the future wireless network is integrated sensing and communication and the processing of the sensing and communication data simultaneously is needed by the algorithms of Machine Learning. Sensing information has the potential to enhance channel estimation, localization and interference management on 6G wireless communication networks and can therefore allocate resources more efficiently [3,37-39]. Transmission parameters are adjusted using Artificial Intelligence algorithms that analyze environmental data that enhances reliability and coverage. Those methods are especially significant to intelligent cities, autonomous transport, and automation of industries, where communication networks need to engage with the physical world. Digital twin networks, edge AI and intelligent spectrum management are commonly used together with integrated sensing and communication algorithms to develop fully adaptive communication infrastructures. The intersection of sensing, communication and computation is one of the most significant technological trends in next-generation networks and advanced Machine Learning methods are necessary to accomplish the intersection.

## 3.2 Application

### Smart Urban Infrastructure and Cities

The creation of smart cities is one of the most important areas of Artificial Intelligence and Machine Learning use in 6G wireless communication networks, where AI-based networks would create intelligent urban infrastructure (with real-time monitoring and automation), and smart decision-making. The wireless networks of the future are likely to provide huge connectivity between sensors, cameras, vehicles and services to the population meaning that the networks have to have intelligent spectrum management, distributed intelligences and ultra-low latency managed communication to be able to operate reliably [36,40-42]. Machine Learning algorithms are highly important in the analysis of

extensive amounts of urban data to facilitate predictive traffic control, optimal energy usage, environmental control, and intelligent public safety systems. By combining edge AI and digital twin networks, the city administrators can model the conditions in the real world and optimize the way the resources are distributed, prior to any alterations in the physical infrastructure. Moreover, integrated sensing and communication technologies can be used to allow conversations between communication systems and the immediate environment, enhancing the situation awareness as well as the effectiveness of the network. Such features indicate that AI-based networks will play a vital role in constructing smart city ecosystems, which are sustainable, efficient and autonomous with the help of 6G wireless communication.

### ADVs and Smart Transportation Systems

One of the key uses of Machine Learning and Artificial Intelligence in 6G wireless communication networks is autonomous vehicles since the transportation systems of the future will need ultra-reliable and ultra-low latency communication to facilitate real-time decision-making. The intelligent transportation systems will be based on the AI-driven networks that will permit the vehicle-to-vehicle, vehicle-to-infrastructure, and vehicle-to-network communication so that cars, drones, and the public transport systems could coordinate their actions safely and efficiently [40,43-44]. Predicting the state of the traffic, planning the route, and controlling the mobility in the highly dynamic environment are done by the reinforcement Learning and edge AI algorithms. The large data rates needed in high-resolution sensing can be offered by terahertz communication and massive MIMO technologies, whereas integrated sensing and communication enables vehicles to sense obstacles and communicate at the same time. Federated learning is an algorithm that allows jointly training models between cars without any loss in privacy, which is why it is applicable to large-scale intelligent transportation. Such trends show that autonomous wireless systems with 6G wireless communication will be at the core of the transformation of the next-generation transportation networks.

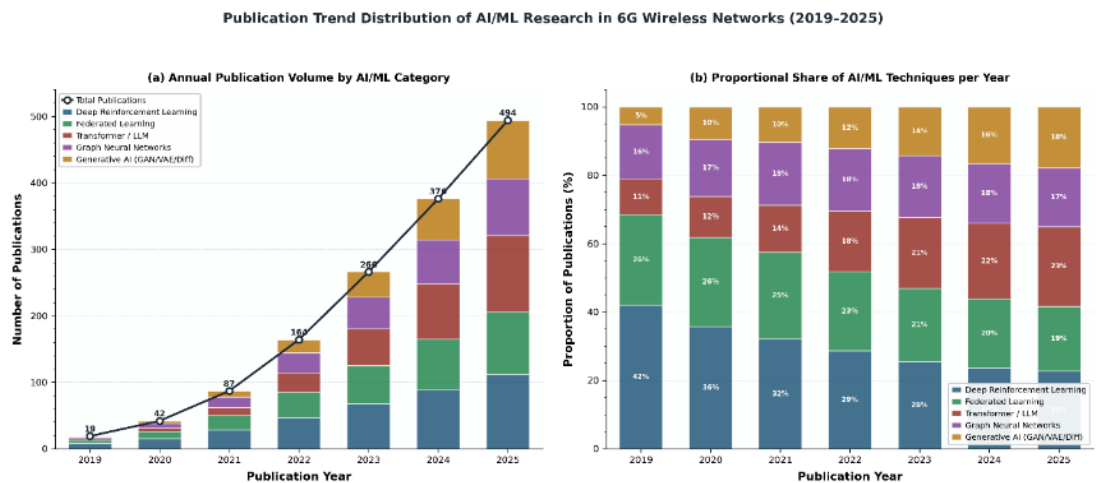


Fig. 3 Publication Trend Distribution (2019–2025)

Fig. 3 shows dual stacked bar charts (absolute + proportional). Panel (a) shows exponential annual growth from ~19 papers in 2019 to ~494 in 2025, with Transformer/LLM surpassing DRL as the dominant technique by 2025. Panel (b) shows proportional share shifting over time — FL and Generative AI are gaining ground while DRL's relative share shrinks, signaling research diversification. The total trend line confirms a compounding growth trajectory reflecting the field's maturity surge.

### Extended Reality, Holographic Communication, and Immersive Media

The most challenging applications to wireless networks in the future are Extended Reality, The holographic communication and immersive media applications, which demand very high data rates, very low latency communication and smart resource allocation. With the help of Artificial Intelligence and Machine Learning algorithms, it is possible to provide semantic communication, adaptive compression, and intelligent bandwidth management, which will provide an opportunity to transmit

large amounts of multimedia data at an efficient price [3,45-48]. Making data processing nearer to the user is another important aspect of Edge AI that makes it important in terms of minimizing latency and is necessary when using virtual reality and augmented reality applications in real-time. Realistic virtual environments can also be engineered through use of digital twin networks, and in such a manner, interact with real-world systems, allowing advanced simulation and training applications. Moreover, intelligent radio access network control is used to dynamically assign network resources to the demand of the users, enhancing quality of service in the most congested environment. The technologies depict that AI-native networks will be required to facilitate immersive communication experiences in 6G wireless communication systems.

#### Smart Remote Medical and Healthcare Systems

One of the most significant fields of application of Artificial Intelligence, Machine Learning, and 6G wireless communication networks is Smart healthcare that can support advanced medical services like remote surgery, constant health control and monitoring, and intelligent diagnosis. The next generation of wireless network should offer ultra dependable and secure communication to accommodate real time delivery of medical information which necessitate smart spectrum management, network automation and distributed intelligence [5,19,49-50]. Edge AI enables medical devices to run local data processing and shorten latency as well as enhance privacy, whereas federated learning enables analysis of collected patient data without sensitive information being exposed. Remote monitoring of vital signs can be performed with the help of integrated sensing and communication technologies that allow identifying the health issue at an early stage. Digital twin networks enable physicians to practice medical procedures and master them in advance prior to the actual operation, enhancing the accuracy and safety. Such applications demonstrate the relevance of AI-based networks to supporting the next-generation healthcare system, which is backed by smart wireless networks.

#### Autonomous Manufacturing Systems and Industry 4.0

It is thought that the adoption of Artificial Intelligence and Machine Learning in 6G wireless communication networks will have a positive effect on the emergence of Industry 4.0, in which intelligent factories will run with very minimal human oversight. The autonomous manufacturing systems demand real-time communication between the robots, sensor, and control units and this can only be guaranteed by ultra-low latency communication and high reliability wireless networks [29,51-53]. Machine Learning algorithms can be used to control predictive maintenance, fault detection, and adaptive control of the processes, which enhance productivity and minimize downtime. Edge AI enables local decision-making by industrial devices, which are less reliant on cloud systems. The digital twin networks are popular in the simulation of the production process and optimization of performance prior to deployment. Moreover, intelligent spectrum management also makes sure that communication resources are efficiently distributed at the settings where many devices are connected to each other. These functions prove that AI-native networks will become one of the enablers of the fully autonomous industrial systems of wireless networks in the future.

#### Non-Terrestrial Networks and Space-Air-Ground Integration

Non-ground networks, such as satellite communications, high-altitude platforms, and unmanned aerial vehicles, emerge as a significant use of 6G wireless communication networks, and they allow connection to the world even in the remotest locations. The complexity of interactions of the terrestrial and non-terrestrial networks demands Artificial Intelligence and Machine Learning algorithms that will guarantee smooth communication between various platforms [54-56]. Smart Radio access networks and distributed intelligence removes the need to allocate resources dynamically in highly diverse environments. Optimal routing and spectrum utilization may be achieved with the help of the reinforcement Learning whereas federated learning may be used to optimize routing and spectrum utilization without exchanging sensitive data. Space-air-ground integration links modes of communication offer high capacity connections that are enabled by terahertz communication and massive MIMO technology. The above developments indicate that AI-powered networks will play a critical role in realizing worldwide smart connectivity in the future wireless networks.

### Smart Internet of Things and Massive Connectivity

The IoT is projected to have billions of connected devices in the next wireless networks and as such, intelligent management is necessary to ensure efficiency and reliability in managing the IoT. With the help of Artificial Intelligence and Machine Learning, the spectrum can be managed intelligently, the allocation of resources can be adapted, and the network can be automated, which gives the opportunity to provide communication to large masses of devices at the same time [57-59]. Edge AI and distributed intelligence minimise the communication overhead by operating on the data at the device level, whereas federated learning provides privacy-preserving cooperation across the devices. IoT devices can also communicate with the physical world through integrated sensing and communication technologies and enhance situational awareness. The algorithms of semantic communication decrease the volume of data transmitted since they concentrate on the meaningful information and not on raw signals. These methods show that AI-native networks are required to enable high connectivity of 6G wireless communication systems.

### Loyalty, Confidentiality and Trusting Wireless Communication

One of the critical application areas in 6G wireless communication networks is security because more autonomous wireless systems are increasingly used and therefore they need higher protection against cyber threats. Intrusion detection, anomaly detection, and secure authentication are conducted with the help of Artificial Intelligence and Machine Learning algorithms and enable networks to react to the attack in real time [9,60-61]. Federated learning and distributed intelligence enhance privacy by ensuring the sensitive data are stored at the network edge. Quantum Machine learning and blockchain-based security are under investigation to increase confidence in AI-based networks. Radio access networks can also be intelligent to detect abnormal behavior and automatically modulate the communication parameters to avert attacks. These methods demonstrate that the security based on AI is going to become a necessity in the future, to have reliable and trusted wireless networks.

### Green and Energy efficient communication systems

Another notable use of Artificial Intelligence and Machine Learning in the context of 6G wireless communication networks is energy efficiency because the future wireless infrastructures have to be high-performing and at the same time a minimum of power usage. Machine Learning algorithms are able to optimize power control, allocation of resources and the network configuration to minimize energy consumption without compromising the quality of service [38,62-63]. Network automation and edge AI enable the devices to work only when necessary, which increases efficiency. AI can also reconfigure intelligent surfaces to direct signals more efficiently to reduce the amount of transmission power required. Digital twin networks give the opportunity to simulate the energy consumption patterns and thus operators can create a more sustainable communications system. Those strategies prove that AI-driven optimization will be important in the future creation of green and sustainable wireless networks.

### Autonomous Network Management Applications and Digital Twin

One of the most progressive applications of Artificial Intelligence and Machine Learning to 6G wireless communication is the digital twin networks that will allow monitoring, simulating, and autonomously controlling the management of complex communication infrastructures. Digital twin systems enable operators to forecast failures, performance optimization, and experimental settings without impacting actual operations by building physical network simulations [64-67]. Machine Learning applications are used to analyze massive amounts of network data and make smart decisions under automated systems. The practice of network automation and self-organizing networks lessens the necessity to have human input so that future wireless networks will act as autonomous wireless systems. The fact that integrated sensing and communication can strengthen the potential of the digital twins to respond to the physical environment is another advantage. Such features suggest that smart networks based on digital twins with AI-native networks will have a crucial role in handling the complexity of the next-generation wireless communication systems.

## Statistical Distribution of 6G Network Performance Gains via AI/ML Techniques

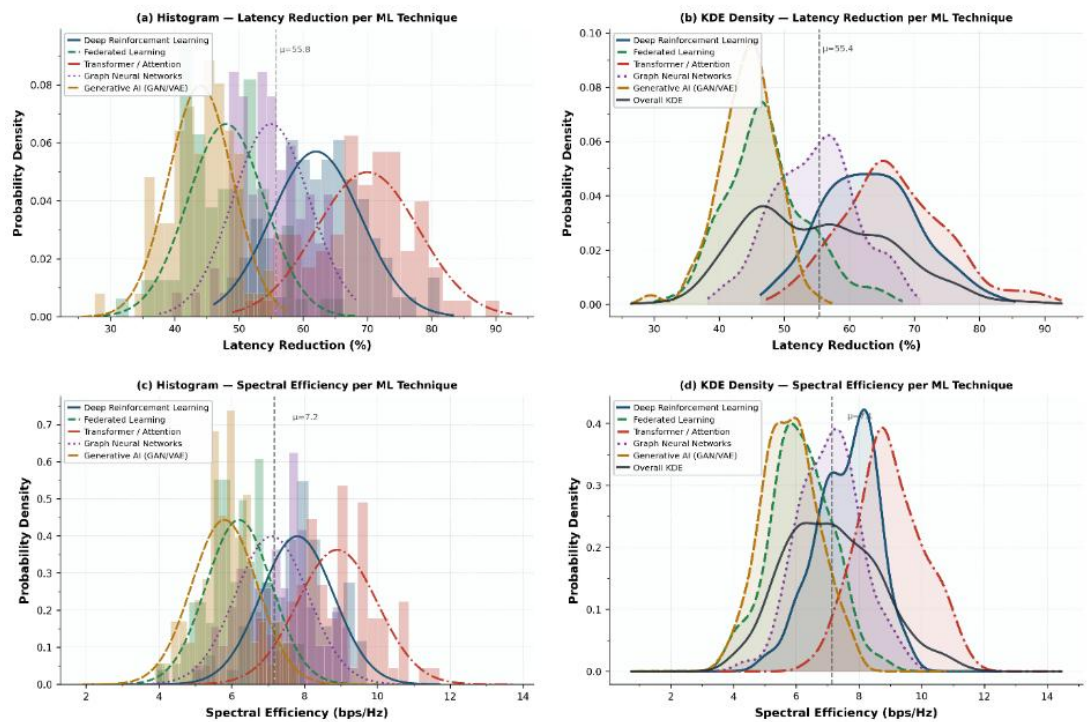


Fig 4 KDE + Histogram Statistical Distributions

Fig. 4 shows a  $2 \times 2$  panel with histogram + fitted normal curves and pure KDE density overlays. Panels (a)/(c) show fitted normal histograms for Latency Reduction and Spectral Efficiency; panels (b)/(d) show smooth KDE densities with fill areas. Transformer/Attention models exhibit the rightmost distribution ( $\mu \approx 70\%$  latency reduction;  $\mu \approx 8.9$  bps/Hz SE), while Generative AI sits leftmost. The pooled overall KDE with vertical mean line provides a field-level statistical baseline for benchmarking.

#### 4. Discussion

Comparison of the AI-based and traditional wireless network architecture

The literature repeatedly proves the fact that the shift toward the use of AI-native networks instead of conventional programmable wireless networks is one of the most radical changes in the history of wireless communication, especially when it comes to the 6G wireless communication systems. The conventional network design is based on rule-based control, fixed configuration and deterministic optimization algorithms that lack the capability to address the complexity of future wireless networks that can be described as ultra-low latency communication, massive connectivity and heterogeneous communication conditions [2,68-70]. Conversely, AI-driven networks place Artificial Intelligence, Machine Learning, Deep Learning, and Reinforcement Learning as part of the network architecture, which allows the creation of autonomous wireless systems that can learn in real-time, adapt, and self-optimize. The comparative study of recent literature indicates that AI-based resource allocation and smart spectrum management are much better resources, spectral efficiency, reliability, and energy efficiency than traditional methods. The introduction of distributed intelligence, edge AI, and federated learning also make it even more scalable as computation can be performed closer to the source of data than the fully centralized one. It is also pointed out in the comparison that AI-native networks are needed to support novel technologies, including terahertz communication, massive MIMO, reconfigurable intelligent surfaces, and integrated sensing and communication, each of which needs adaptive algorithms capable of reacting dynamically to changing situations. These results show that the introduction of the Artificial Intelligence and Machine Learning is not only positive but it is essential to

meet the performance demands of the next-generation networks and to introduce the creation of the fully autonomous communication infrastructure.

#### AI Integration Tools and Frameworks In 6G Wireless Communication

The analysis of the current literature shows that there are a great number of tools, simulator platforms, and software frameworks that can help implement Artificial Intelligence and Machine Learning in 6G wireless communication systems. The frameworks of developing AI, the simulation environment of the network, and digital twin platforms are becoming increasingly used by researchers to design, test, and optimize AI-driven networks in the real world [16,71-73]. Deep Learning libraries and Machine Learning toolkits are ubiquitous in implementing intelligent radio access network algorithms, and the terahertz communication, massive MIMO and non-terrestrial networks can be evaluated in realistic conditions using specialized wireless communication simulators. Digital twin networks provide a very strong solution to complex communication infrastructure modeling, which allows predictive analytics, optimization of performance, and fault detection. There are also edge AI systems that are designed to operate in real-time inference and distributed intelligence in the base stations and user devices, which shortens latency and enhance privacy. Moreover, the federated learning systems enable the cooperative training of many devices without the transmission of raw data, which is crucial to privacy-preserving AI-native networks. The growing number of open-source AI platforms and high-performance computing platforms have enabled intelligent wireless system research to go faster, enabling researchers to test with more complex algorithms including Graph Neural Networks, semantic communication models, and quantum machine learning methods. These tools will be highly important in the future of wireless networks because they will allow building prototypes quickly, run mass testing, and implement AI-based solutions efficiently.

#### Algorithms of the Intelligent Resource Allocation and Network Optimization

One of the most widely researched issues in the field of 6G wireless communication is on the use of Machine Learning and Artificial Intelligence techniques in the allocation of resources and optimization of networks because of the significance of efficient spectrum utilization, power regulation, and traffic control in future wireless networks. Supervised Learning, Unsupervised Learning and Reinforcement Learning are common methods of optimising communication parameter depending on real-time information gathered on network equipment [74-77]. Deep Reinforcement Learning is especially useful in dynamic environments in which optimal choices need to be taken at all times, including intelligent radio access networks and self-organizing networks. Federated learning techniques enable distributed learning involving multiple devices, which lowers the communication cost and enhances scalability. Graph Neural Networks are becoming popular in the modeling of complex relationship between nodes in a network to allow a more relevant optimization in ultra-dense communication situations. Even semantic communication schemes are in the works to minimize the needs of data transfer through concentrating on meaningful data rather than mere signals to enhance efficiency in situations where there are large numbers of connectivities. The combination of sensing and communication methods offer extra data regarding the surrounding and the decisions made by Machine Learning algorithms are more precise. These techniques prove that it is important to have smart optimization algorithms that can facilitate autonomous wireless systems which can be used to support the high-performance standards of 6G wireless communication networks.

The 6G wireless communication networks make use of AI models in the following types

The findings of the literature review indicate that a broad range of Artificial Intelligence models are being implemented on various aspects of the 6G wireless communication network and each has certain benefits based on the application. DNNs have found extensive application in channel estimation, signal detection, and beamforming optimization, and Convolutional Neural Networks have also performed well in processing spatial data in massive MIMO systems [78-81]. Transformer-based and Recurrent Neural Networks are applied to predict traffic, mobility, and time-series. Resource allocation, network slicing and power control are also tasks that are usually addressed using Reinforcement Learning models to achieve autonomous decisions in dynamic environments. Distributed learning Federated learning models provide enhanced privacy and scalability because more than two devices can learn an identical

model without sharing raw data. GNNs have been applied especially to model the network topology and maximize routing in intricate communication infrastructures. The terahertz communication and non-terrestrial networks are also using quantum machine learning and hybrid AI models as the potential solutions to high-dimensional optimization problems. The variety of AI models is a measure of the complexity of the next-generation networks and the need to have flexible and adaptive AI-native architectures that can be flexible enough to combine various learning techniques in parallel.

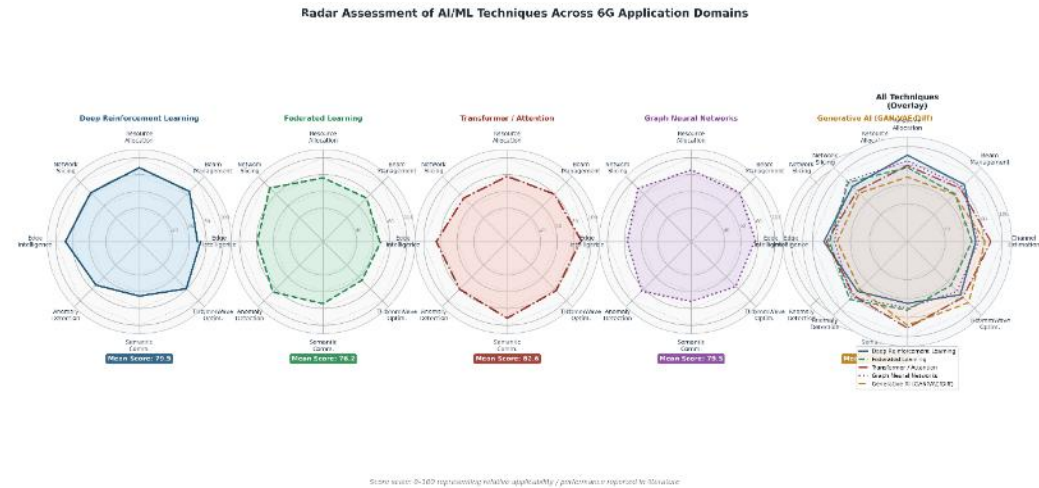


Fig. 4: Radar Chart: AI/ML Across 8 6G Application Domains

Fig. 4 explains a multi-panel radar (spider) with 5 individual subplots + 1 composite overlay. Eight 6G application axes are evaluated: Channel Estimation, Beam Management, Resource Allocation, Network Slicing, Edge Intelligence, Anomaly Detection, Semantic Communications, and THz/mmWave Optimization. DRL dominates Resource Allocation (91) and Beam Management (85); Transformers lead Channel Estimation (88) and Semantic Comms (91); Generative AI leads THz/mmWave Optimisation (91). The composite overlay makes cross-technique comparison immediate and visually compelling for journal figures.

#### Practical difficulties in AI-assisted 6G Wireless Communication

Regardless of these achievements, the literature outlines a number of challenges that require to be overcome before artificial intelligence and machine learning can become a full-fledged part of the 6G wireless communication networks. The high computational complexity of the Deep Learning and Reinforcement Learning algorithms is one of the most crucial challenges, as it needs efficient hardware acceleration and energy-efficient design to allow operating it in real-time [6,82-85]. The second issue is that there are no standard frameworks of AI-native networks, thus it is hard to interoperate across various devices and network elements. Privacy and security of data is also a significant issue, especially in distributed intelligence systems, where sensitive data can be handled in different locations. Additional complexity is brought by the integration of terahertz communication, non-terrestrial networks, as well as integrated sensing and communication, which necessitates an advanced set of algorithms of Machine Learning that can manage highly dynamic environments. Network automation poses the problem of reliability as autonomous wireless systems should be capable of functioning safely even in the absence of humans. Ethical issues connected to explainable AI and reliable Machine Learning are gaining more significance as communication networks grow freer. These issues show that more studies should be conducted to come up with scalable, secure, and energy-efficient AI-based solutions to the future wireless networks.

#### Opportunities Enabled by AI-Native 6G Wireless Networks

The findings demonstrate that implementation of Artificial Intelligence and Machine Learning in 6G wireless communication networks opens a wide range of possibilities in enhancing performance, efficiency, and flexibility. The networks based on AI will be able to adapt to the changing conditions automatically, allowing the opportunities of intelligent spectrum management, dynamical resource

assignment, and predictive maintenance [86-88]. Edge AI and distributed intelligence enable real time processing in proximity to the user with reduced latency and better quality of service. Digital twin networks allow the operators to model the behavior of the network and optimize its performance in advance. Intelligent surfaces can be reconfigured and this enables wireless environments to be dynamically controlled, enhancing coverage and minimizing interference. Semantic communication minimizes the quantity of data that needs to be sent enhances efficiency in huge connectivity cases. These possibilities prove that AI-native networks will make it possible to create new applications holographic communication, smart cities, autonomous vehicles, and intelligent healthcare systems. This capability of integrating various methods of AI in one network design will be one of the determinants of the realization of the fully autonomous wireless network of the future.

#### Experimental Testbeds and Real-World Implementations

According to recent studies, a number of experimental testbeds and pilot projects have been created to test the Artificial Intelligence and Machine Learning in 6G wireless communication networks. The implementations are usually based on digital twin networks, edge AI systems, and software-defined radio systems which are used to emulate real-world communication worlds. Massive MIMO and terahertz communication Testbeds are utilized to test high-frequency transmission and high-level beamforming. Non-terrestrial network experiments This is a form of network testing that involves satellite communication, aerial platforms, and terrestrial networks to show the global connectivity. The system of network automation based on AI is tested in the conditions of smart cities to analyze the management of traffic in real time and optimization of energy. Such experimental implementations offer useful information about the applicable challenges of implementing AI-native networks as well as enable scientists to come up with more efficient algorithms. The number of testbeds is on the rise, which means that the research on 6G wireless communication is ceasing to be just theoretical and shifting to practical use.

#### The Future of the Wireless Ecosystems and the influence of AI and Machine Learning

Artificial Intelligence and Machine Learning collaboration on the 6G wireless communication networks can be seen not only in technical advancement but also in the overall state of the wireless ecosystem, including industry, society, and digital infrastructure. The networks powered by AI allow novel business models that are grounded on smart connectivity, intelligent services, and autonomous systems. Smart cities, smart transport, and Industry 4.0 are based on the reliable and adaptive communication networks that can provide the chance to process data in real-time. The distributed intelligence enables the devices to act on their own, and at the same time collaborate with the network, which enhances scalability. Machine Learning-based green communication methods decrease environmental impact and energy usage. The mentioned changes signal that AI-native networks are going to be the cornerstone of the future digital society, where high-performance, high reliability, high-security applications will be supported.

#### Policies, Regulations and Standardization Issues

Policies, regulations, and standardization are also another important role the literature emphasizes in developing Artificial Intelligence and Machine Learning in 6G wireless communication networks. With more autonomy in networks, the regulatory framework is to be involved with the issues of privacy, safety, and the ethical application of Artificial Intelligence. There should be standardization in order to make different devices, vendors, and network components interoperable. There is the need to international cooperation to specify frequency bands in terahertz communication and non-terrestrial networks. Energy efficiency and environmental sustainability constitute the other policies that are coming to prominence due to the increasing size and complexity of the wireless infrastructures. Such regulatory factors will play an important role in identifying the speed of AI-native networks implementation.

## The Future of AI-based 6G Wireless Communication Studies

The findings of the literature review suggest that in the future, studies in the field of Artificial Intelligence and Machine Learning in 6G wireless communicational networks would center on the creation of fully autonomous wireless systems that are able to self-learn, self-heal and self-optimize. Quantum machine learning, semantic communication and integrated sensing and communication are likely to make it to the list of hot research topics with high citation potential in the future. Federated learning and edge AI will keep on advancing to facilitate distributed intelligence and privacy-preserving optimization. Predictive network management and real-time simulation will be possible with digital twin networks. Reconfigurable intelligent surfaces and terahertz communication will offer new possibilities of high-capacity transmission. Explainable AI, trustworthy Machine Learning and energy-efficient algorithms are also to be developed in future studies in order to make the next-generation networks reliable and sustainable. These tendencies prove that Artificial Intelligence and Machine Learning will become the main two technologies that will promote the development of the further wireless networks beyond 5G and even to the period of the completely intelligent 6G communication system

## 5. Conclusion

The presented literature review directed by the PRISMA 2020 methodology offers a systematic and clear overview of the current studies on the Artificial Intelligence and Machine Learning in 6G wireless communication networks, which also encompass the change in the traditional programmable networks to a predominantly AI-based architecture that can independently make decisions, optimize its processes, and manage its resources. The examined literature confirms that the further development of wireless networks will necessitate self-organizing networks, intelligent radio access network control, and AI-based resource allocation algorithms to accommodate the record performance requirements of ultra-low latency communications, massive connectivity and terahertz frequency communications. Machine Learning, Deep Learning and federated learning have become enablers that enable networks to learn and predict traffic behavior and dynamically optimize spectrum use, enhancing efficiency, reliability and scalability in next-generation networks. It is also demonstrated in the literature that integrated sensing and communication, customizable intelligent surfaces, digital twins' networks, and edge AI are becoming inherent elements of intelligent wireless infrastructure, allowing real-time monitoring, predictive maintenance, and self-configuring network creation.

The other significant observation of this review is that the process of transition to AI-driven networks is strongly associated with the design of smart security protocols, distributed intelligence, and privacy-preserving learning algorithms, which are needed to keep trust, reliability, and resiliency within highly complex 6G wireless communication settings. The significance of explainable AI, trustworthy Machine Learning, and sturdy cyber-physical security systems grows exponentially as wireless systems grow more autonomous, and especially in sectors that consist of participating smart cities, connected vehicles, remote healthcare, industrial automation, and extended reality. The literature also suggests that network automation underpinned with edge computing and cloud-native architecture will facilitate real-time decision making at various levels of the communication structure and enable future wireless networks to be run with a minimum human input and with high performance and energy efficiency. The latter supports the conclusion that the integration of Artificial Intelligence, communication engineering, and data-driven optimization are what will determine the fundamental design philosophy of wireless networks in the future (not 5G).

The review also reveals that there are a number of research gaps that need to be bridged before we are able to achieve the full autonomy of 6G wireless communication networks. High computational complexity of Deep Learning and full-scale Machine Learning models are one of the greatest challenges that demand effective hardware acceleration, distributed processing, and lightweight AI algorithms that can run on real time. The second problem is the inability to standardize frameworks of AI-native architecture, which makes it difficult to interoperate among components of the network and also makes it slow when it comes to implementing large-scale AI-based systems. Moreover, the introduction of

terahertz communication, non-terrestrial networks, and intelligent spectrum management creates new challenges related to the propagation of the signal, the resource scheduling, and cross-layer optimization which demand sophisticated AI-based solutions. Ethical factors, privacy of data and regulations are also of concern but specifically in cases where autonomous wireless systems engage in real time decision making that may affect critical infrastructure. The future research must thus aim in creating scalable AI-based networks which merge federated learning, edge AI, digital twins networks and intelligent radio access network control to create the fully adaptive and self-evolving communication systems. More focus should also be placed on the energy-efficient Machine Learning models, and secure distributed intelligence, and explainable AI techniques that are necessary to make next-generation networks reliable, transparent, and sustainable. Moreover, the implementation of intelligent 6G wireless communication networks will require interdisciplinary cooperation among communication engineering, Artificial Intelligence, hardware design, and cybersecurity research to make the implementation of these networks faster. The results of this review prove that the difference between successful integration of Artificial Intelligence and Machine Learning will be the determinant of successful accomplishment of the vision of autonomous, resilient, and high-performance 6G wireless communication networks that are able to support the digital society of the future.

### **Author Contributions**

GS: Conceptualization, visualization, writing original draft, writing review and editing. SKS: Analysis, data collection, methodology, writing review and editing.

### **Conflict of interest**

The authors declare no conflicts of interest.

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