A Comprehensive Survey on 6G Wireless Communications: Fundamentals, Potential Applications, Technologies, Challenges, and Research Directions

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Abstract: In the present decade, there is an exponentially growing demand for wireless connectivity. This is because of the sudden growth in the emergence of the Internet of Things (IoT) and the extensive utilization of smart devices. This requires low latency and ultra-reliable communication for better advancement. This has influenced researchers to develop an advanced version of the existing wireless network called the sixth generation (6G) for the future cellular system. It utilizes advanced technologies, such as Artificial Intelligence (AI) integration and terahertz frequencies, to provide low latency and high-speed communication. At present, the 6G is not operational, whereas the investigation and evolution are in progress, and are expected in practice between 2027 and 2030. Hence, it is significant to offer a potential vision of 6G and the major facilitating technology for realizing the future network. Therefore, this work initiates a comprehensive survey of the 6G wireless communication network's future evolution. At first, the framework investigates the design principles and objectives for 6G, along with the operation principles and discussion of each technology. It also involved the research on the present state-of-the-art model, envisioned potential application and the corresponding technical challenges. For a better understanding, the merits and demerits of the standard technology are determined. Finally, the work ended with a detailed conclusion of research limitations and possible solutions in 6G that enable critical technologies.

Keywords: 6G Network: Wireless Communications; Artificial Intelligence; Enabling Technology; Positive and Negative Impacts; Research Gaps and Possible Solutions

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Nomenclature

Abbreviation	Description
6G	Sixth Generation Wireless Communication
AI	Artificial Intelligence
IoT	Internet of Things
THz	Terahertz
VLC	Visible Light Communication
DSS	Dynamic Spectrum Sharing
MIMO	Multiple Input Multiple Output
RIS	Reconfigurable Intelligent Surface
ECC	Error Correcting Codes
IBFD	In-Band Full-Duplex
ISAC	Integrated Sensing and Communication
SDN	Software-Defined Network
MEC	Mobile Edge Computing
Edge AI	Artificial Intelligence applied at the network edge
QC	Quantum Communication
QKD	Quantum Key Distribution
MC	Molecular Communication
WET	Wireless Energy Transfer
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vessel
SAGSIN	Space-Aerial-Ground-Sea Integrated Network
SU	Secondary User
PU	Primary User
OAM	Orbital Angular Momentum
DDPG	Deep Deterministic Policy Gradient
DRL	Deep Reinforcement Learning
CNN	Convolutional Neural Network
LSTM	Long Short-Term Memory
CNN-LSTM	Hybrid model of Convolutional and LSTM networks
MADRL	Multi-Agent Deep Reinforcement Learning
MAC	Media Access Control
GNN	Graph Neural Network

MARL	Multi-Agent Reinforcement Learning
V2X	Vehicle-to-Everything Communication
V2V	Vehicle-to-Vehicle Communication
ADN	Autonomous Driving Network
NFV	Network Function Virtualization
NLOS	Non-Line-of-Sight
RLC	Resistor–Inductor–Capacitor Circuit
CST	Computer Simulation Technology
RF	Radio Frequency
RAN	Radio Access Network
SEE	Secrecy Energy Efficiency
TS	Traffic Steering
IRS	Intelligent Reflecting Surface
NOMA	Non-Orthogonal Multiple Access
AP	Access Point
DNN	Deep Neural Network
DT	Digital Twin

1. Introduction

In the current decade, large-scale commercial deployment has been achieved by the 5G wireless network. This 5G system faces significant challenges due to the sudden development of data-centric intelligent systems [1]. However, to meet the future demand, the research and development of government, academia and industry has given more attention to 6G wireless communication systems. While differentiating the 5G network, 6G offers lower communication delay, maximum network speed and wider coverage depth [2]. In addition, the 6G system provides faster and more reliable connectivity to support new applications like virtual reality and the metaverse [3]. It also involves space communication to generate the omnipresent wireless network based on the significance of true wireless ubiquity [4]. Further, AI become a significant part of the 6G era, which depends on mining big data for learning and training/. This tends to improve the computing power to achieve a better transmission rate and achieve more flexibility based on continuous learning [5]. In future, the 6G network will have to deal with excessive device connections and intense data traffic [6]. The control and management of these data in real time results in maximum complexity.

Hence, to efficiently attain the service characteristic, the dynamic allocation of the wireless resource becomes a significant challenge for the 6G network [7]. With the involvement of big data techniques and AI, key technologies and applications become highly integrated to enable full applications [8]. Additionally, the dynamic correlation enabled by AI for caching, networking and computing resources enhances network performance. While developing the 6G network, a strong security framework is required, incorporating both network and physical layer security [9]. With current trends, the 6G network must be thoroughly investigated to enable effective technologies, since the wireless channel is considered the foundation of the system, optimization process and performance evaluation [10]. In this framework, the characteristics and measurement of 6G wireless channels are comprehensively evaluated for various scenarios, along with general standards and future challenges.

Contributions: The significant contributions of this survey are listed as follows.

- To outline the general knowledge of 6G wireless systems along with the importance of architectural evolution for future technologies. This study aimed to discuss the key fundamental performance of the 6G network by investigating all the relevant technologies to satisfy the requirements of future 6G networks.
- To highlight the design principles and explore some research technologies that may be essential for 6G. The advancements and limitations of these methods are also discussed to provide future work direction for 6G applications.
- To achieve 6G goals, technologies and applications are summarized along with an understanding of the research gaps and challenges in various scenarios. This research analysis supports the easy development of future networks.

Organization: The rest of the survey is arranged as below. Section 2 describes the network architecture with the key technologies that are significant to the success of 6G. Section 3 presents the various research activities of 6G mobile communication and the wide range of use cases with their merits and demerits. Section 4 discusses the limitations and the research direction in attaining the goal of 6G. Finally, Section 5 concludes this survey.

2. Key Technology Points and Network Architecture of 6G Wireless Communication Systems

2.1 System Design

The innovation of the 6G network is to enable access to both the real and virtual worlds by providing seamless coverage of global intelligence to all users. The 6G system aims to enhance the SAGSIN by involving both terrestrial and non-terrestrial networks. The main purpose is to implement SAGSIN with limitless coverage. There are four segments in SAGSIN, which help in processing the data independently or transferring the information cooperatively with each other to achieve high-quality data communication for the user.

Several types of satellites are included in the Space network based on the ground infrastructure [11]. It incorporates the control center with the ground station. In the space network, the low-orbit satellite is more significant because of our advancement in achieving high performance with minimum latency. However, there the security threats in the space network, such as vulnerable satellite signals that tend to eavesdropping. The characteristics of the satellite channels are determined by integrating large-scale MIMO, which offers low-complexity channel estimation.

The high and low altitude platforms comprise the Aerial network, which contains hydrogen balloons, UAVs, airships and aircraft. When compared with the satellite network, the air network is more flexible and has lower response time for communication. The efficient information interaction is enabled by the UAV platform through the utilization of base stations and antennas. Due to the higher mobility of UAVs, they frequently change the topology to design an efficient mechanism. This ensures network security by offering low latency and high throughput network access.

The cellular wireless network is comprised of the Terrestrial network, including the ground data processing centre, ground internet, satellite station and ground station. In general, ground networks suffer from human interference and natural disasters. It is significant to minimize resource allocation issues and to understand suppression communication techniques to address channel interference. In addition, security is ensured by taking appropriate measures for end-to-end communications.

The underwater fixed sensors and USVs are integrated into the Undersea network. Some of the unique challenges faced by the sea network include uncertainty in the marine environment and signal fading in communication [12]. To address these limitations, sea-based communication models are designed to manage the complex environment and improve connectivity for a large number of users in maritime communication. Additionally, the required security measures should be taken to solve these issues by involving underwater node authentication and encrypted communication. The architecture of the 6G network based on SAGSIN is shown in Fig.1

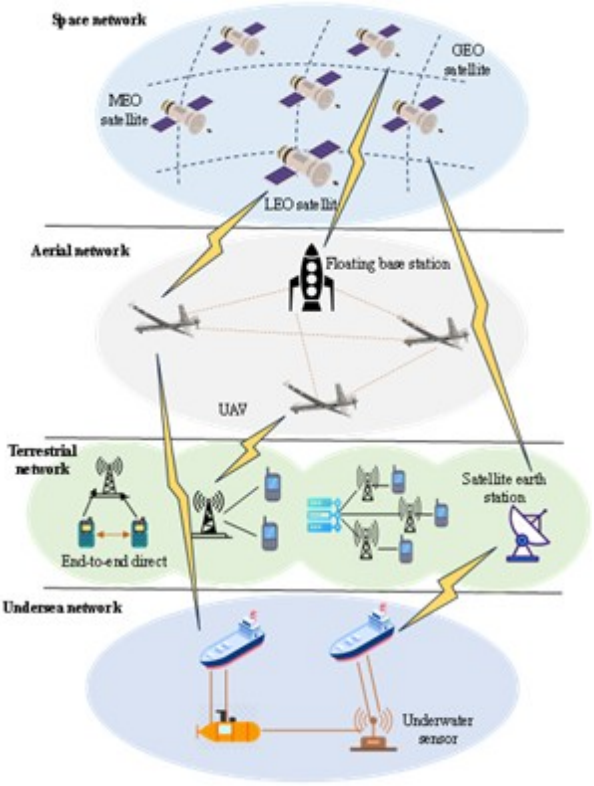

Fig. 1. System diagram of 6G network based on SAGSIN

2.2 Key Technologies in 6G

The major reason for implementing 6G is to improve the communication system through effective computing, amalgamating communication, security and sensing functionalities. While constructing 6G, 16 prospective key technologies are utilized and are detailed below.

2.3 New Spectrum Resource

The segment of the electromagnetic spectrum used is the THz waves, which are defined by high frequencies ranging between 1011 Hz to 1013 Hz. THz has the characteristics of pronounced molecular absorption, broad bandwidth, high frequency and substantial path loss [13]. Compared with infrared radiation, THz provides a higher transmission bandwidth.

Information transmission is involved in VLC by modulating the spectrum in the visible light range. The general wavelength used for illumination is between 360 to 760 nm. This technology also serves as an energy source. High-speed data reception and energy harvesting are attained by employing solar cells.

DSS is considered to be an adaptable strategy, which involves a hierarchical access structure to solve the issue of spectrum scarcity. The architecture includes both SUs and PUs. It enhances spectral and energy efficiency based on its pivotal model in the 6G communication system.

2.4 Wireless Access Technologies

Ultra-massive MIMO is characterized by the use of a greater number of antennas, which are allocated to each user and tend to increase in count. It has the potential to attain maximum spectral and energy efficiency based on adaptable network coverage. For the 6G system, spectral efficiency is increased by 10-fold. Thousands of antennas are employed in the wireless environment, significantly improving signal strength and network coverage.

OAM refers to the angular momentum essential for electromagnetic waves, which propagate in a circular motion. Based on spatial arrangement, the motion forms a vortex beam in the emission phase. The OAM technology delivers high data rate services across the communication modalities.

RIS are predicted to use two-dimensional electromagnetic metamaterials. The metasurface comprises multiple reflective elements, known as meta-atoms. It tends to offer minimum energy consumption for real-time control at a lower cost.

Channel coding, also known as ECC, is employed with shorter code lengths in the 6G communication system to ensure ultra-high reliability and ultra-low latency [14]. Novel coding is also combined with a new iterative retransmission scheme.

IBFD allows simultaneous transmission on the same frequency band. It enables higher spectral efficiency by extending the capacity of wireless transmission. In addition, it supports opportunistic wireless sensing and integrated communication through radar-based systems.

2.5 Smart Network Technologies

Based on software and hardware resources, ISAC performs awareness functionalities and synergizes communication. Efficient spectrum use is guided by synergy in energy consumption and time management.

SDN plays a major role in 6G by facilitating refinement, especially in tandem with edge computing advancements. Its flexible configuration allows for more effective network control.

AI is included due to its adaptive learning and robustness capabilities, enhancing the communication system through intelligent optimization management. AI forecasts the behavior of wireless channels by analyzing propagation environment parameters.

A nascent framework known as Edge AI is introduced to harmonize network communication. The combination of MEC and AI capabilities provides seamless orchestration. Latency is reduced by AI while improving privacy safeguards.

2.6 More Communication Technologies

In 6G communication, QC plays a critical role, functioning under the principles of quantum physics [15]. It achieves secure transmission and data encoding, offering unbreakable security.

MC represents an unconventional paradigm that uses molecules for transmitting, receiving and encoding information. It enables communication by regulating specific molecular species.

WET incorporates several key elements in 6G to support a zero-energy paradigm. This compelling technology provides sustainable power to streamline service operations and maintenance, helping reduce emissions in a stabilized network. The key technology for designing the 6G communication network are shown in Fig.2

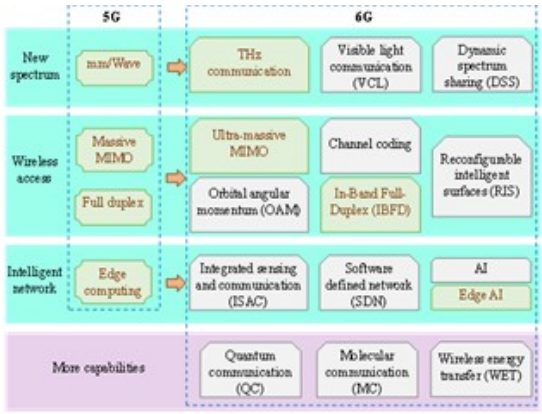

Fig. 2. Key technology structure for 6G communication network

3. Related Works of 6G Wireless Communication System with Merits and Demerits

3.1 Existing Works

There are some new technologies developed in previous research work that significantly enhance the performance of 6G wireless communication networks, which are detailed below for the comprehensive analysis.

In 2025, Shahwar et al. [16] designed an innovative architecture using DRL to improve the energy efficiency and security in IRSs. The two-stage policy learning was initiated by the usage of DDPG for optimizing the SEE. The initiated model ensured secure communication, and it was demonstrated by extensive simulations.

In 2023, Omar et al. [17] proposed the Fly-IRS-based THz communication system to enhance the capacity of the framework. A K-means clustering algorithm was proposed in this

work to address the issues based on optimizing the DDPG in the IRS phase for better determination. The rate of system data maximized from the demonstration of simulation results to enhance the capacity of the system than other conventional algorithms.

In 2023, Nguyen et al. [18] developed a channel estimation model using the Convolutional LSTM for the wireless communication system. The benefits of both networks were utilized to evaluate the spatio-temporal features. The superiority of the model was evaluated by differentiating it from the other standard approaches. The outcome revealed that the performance accuracy in terms of error measures was minimized for the suggested approach.

In 2022, Montaser et al. [19] initiated a neural network model for determining the meta-surface response. Several scenarios were analysed to show how the initiated model performed. The implemented network can predict and learn tasks for better analytical simulation. The initiated model works well for the defect tolerance and performing hundreds of RIS in installing the 6G distributed system.

In 2024, Kavehmadavani et al. [20] proposed a scheme for TS by investigating the RAN for enhancing the overall performance. The diverse service was managed effectively using the proposed algorithm, which enhanced the performance through effective infrastructure. To solve this limitation, different channel conditions and dynamic traffic demand were fulfilled by the optimization architecture with a multi-layer model structure.

In 2023, Paolini et al. [21] introduced an AI-assisted, self-learning and autonomous framework for enhancing 6G security that was more reliable and resilient for mitigating the threat without disrupting general use. The 6G base station was deployed to discover the service based on the implemented model in regard to the cybersecurity mechanism.

In 2024, Ferreiro et al. [22] developed a THz-aided network for predicting the visibility among the APs by reducing the blockages based on network availability. The initiated neural network for forecasting AP visibility probability in which it avoids unnecessary reconfiguration. The present state-of-the-art demonstrated that the experimental outcome of the developed approach attained better results.

In 2025, Madhavan et al. [23] introduced a federated learning-based model along with the algorithm for optimizing the resource allocation to enhance the edge cloud. The energy consumption and latency were significantly reduced by the designed model. It also tackled the limitations of 6G and enabled efficient resource utilization.

In 2024, Muteba et al. [24] examined the potential of the DT to function as a novel model for the 6G communication predictive maintenance. With the demand for the 6G network, there was a need for a reliable maintenance model. The analysis and the monitoring were possibly achieved by the seamless integration of DTs to simulate the 6G network in real-time.

In 2023, Zhang et al. [25] proposed an intelligent routing algorithm for energy prediction in wireless sensor networks with 6G. The scheduling algorithm and node coverage in the network transmission performed the overlap based on the energy prediction. The clustering algorithm solved the issues in the energy-efficient utilization to predict the process. The path selection was performed by the optimization algorithm with an involved clustering mechanism, which enhances the fault tolerance.

In 2024, Agila et al. [26] introduced reinforcement learning and GNN for solving the spectrum-sharing problem in 6G. The characteristics from the communication were extracted using the GNN and it was taken into account for the neighbour's observation. The spectrum access was modelled in multiple links from the present progress to exploit the multi-agent problems. The optimal results were demonstrated from the extensive simulation.

In 2025, Mande et al. [27] presented a sweep line algorithm to tackle the problems in the Euclidean space to improve the security of the resource handling in V2X communication. The greedy method was used here to perform the resource distribution strategy based on exchanging the user's participation. The optimal resource was determined by the presented algorithm by taking the multi-level approach.

In 2024, Haque et al. [28] adopted CST for simulating the RLC circuit in ADS. The model achieved the peak gain with better efficiency with comparable reflection coefficients. The isolation of the antenna was predicted accurately by the supervised regression technique. The smallest error was demonstrated by the gradient boosting regression using the machine learning models. The variance scores and R-squared indicated the isolation prediction.

In 2025, Alwakeel et al. [29] implemented a novel architecture for 6G beamforming that presented the virtualization model to improve MIMO management. The SDN combined with the algorithm model to allocate the beamforming dynamically. Thus enhanced the high-density adaptability for optimizing the signal-to-noise ratios. The overhead of hardware was minimized

by the virtualizing beamforming control to facilitate seamless integration.

In 2022, Sun et al. [30] proposed a combinational model for enhancing malware detection and malicious traffic based on the provided dataset characteristics. The investigation used real data to improve the performance of the algorithm for better detection results. General statistical calculations were used to characterise and provide a promising result.

3.2 Merits and Demerits

In wireless communication, 6G provides promising advancements with increased potential benefits. It aims to offer massive connectivity with low latency across various technologies. Although these technologies show considerable advancements, they also present some limitations. The merits and demerits of the techniques from various research studies are given in Table 1.

Table 1. The features and challenges in the existing literature works

Citation	Year	Author [citation]	Methodology	Features	Challenges
[16]	2023	Shahwar et al.	DDPG	The SEE has been optimized using this model, which can adapt easily to real-time environmental changes and provide efficient communication.	The model tends to overestimate because it does not consider the non-ideality in achieving SEE.
[17]	2022	Omar et al.	Fly-IRS assisted 6G THz	It improves the system capacity by enhancing the system data rate and reducing the outage probability to achieve a satisfactory ratio.	The energy consumption and the flight duration of UAV are neglected in incase of UAV flies at constant altitude.
[18]	2024	Nguyen et al.	CNN-LSTM	It provides a robust result even for the differentiation in the RIS-NOMA system parameter.	Due to the unavoidable energy dissipation, the model is infeasible for practical hardware.
[19]	2023	Montaser et al.	Neural network	It has better generalization capability. It has improved the accuracy by reducing the error rate.	It tends to overfitting and has higher data requirements. It limits interpretability and transparency.
[20]	2024	Kavehmadavani et al.	LSTM-MADRL	It is suitable for a larger timescale to achieve collaborative decisions for intelligent TS for the 6G network.	It increases difficulty and translates to higher training time and maximum resource requirements.
[21]	2025	Paolini et al.	Autoencoder	The malicious packets in the network are detected using this model to provide robust real-time security for the autonomous network.	It is complex to interpret the latent space in achieving the perfect outcome.
[22]	2024	Ferreiro et al.	Neural network	The unnecessary reconfiguration is avoided by the AP reselection with a probability threshold and tends to predict the probability of future user AP visibility.	The accuracy and the generalization of the model are mainly affected by the quantity and quality of the data.
[23]	2023	Madhavan et al.	WPPFL-RS	It efficiently solves the issues in 6G edge computing by optimizing resource allocation and enhancing the cyber-twin technology.	It leads to maximising the communication overhead and faces difficulty in the distribution of diverse data.
[24]	2024	Muteba et al.	DT	The real-time 6G network is simulated by the model and makes it possible to analyse and monitor.	It requires customization and tends to potentially high cost.
[25]	2025	Zhang et al.	Clustering algorithm	In the wireless system, the fault tolerance is enhanced by this model in the transmission of huge dynamic data.	The sensor node distribution range is not ensured for varied working environments.
[26]	2024	Agila et al.	MARL-GNN	It has satisfactory scalability along with better extraction of different types of communication.	It stems from the inherent complexity of coordinating multiple agents for a dynamic 6G network.
[27]	2025	Mande et al.	NNAGbRD-V2V-SLM	The V2X communication and the V2V management are securely handled by this approach.	It is complex to perform in dynamic network conditions.
[28]	2022	Haque et al.	Supervised regression machine learning	It effectively predicts the antenna isolation by accessing the different score criteria.	For the real-world application, some of the challenges like fabrication tolerance and material flaws occurred because of the environmental influence on THz.
[29]	2023	Alwakeel et al.	ADN and NFV	It tends to optimal beamforming parameters and flexible control over dynamic network conditions.	It device lags with the seamless and efficient connectivity.
[30]	2022	Sun et al.	Machine learning	It practically evaluates the malicious network traffic.	It has fewer security concerns.

4. Limitations and Challenges for Wireless Systems with its Future Solution

4.1 Research Challenges

Some of the limitations in the present technology that indicate future research directions are explained here. The 6G system is not only used for data communication purposes, it also supports user-specific services [31]. Therefore user privacy and seamless security are critical for 6G. It also suffers from threats related to MAC such as malware, relay attacks and DoS attacks. For the efficient and successful implementation of the 6G network, machine learning and deep learning play a significant role [32]. The machine learning models used in the existing literature face challenges like resource constraints, high interference, security concerns and wireless channel complexity. The integration of the model needs to face obstacles in training and processing the data for high throughput [33]. The transferability of the model is affected by the degree of the match between the target and source domain.

RF-based communication utilizes the NLOS path, which suffers from losses due to obstruction in NLOS [34]. QKD improves the privacy and security in 6G networks based on quantum mechanics to generate secure communication. However, it has complexity in infrastructure and scalability. Backpropagation is a major issue, addressed using neural networks. However, patching models are not fully capable of resolving this complexity [35]. Wireless communication often collects big data for training neural networks. It becomes critical to effectively train the model with minimal reliance on big data.

4.2 Issues and its Possible Solutions

The summary of the existing models and the possible solutions is provided in Table 2 for enhanced clarity.

Table 2. The limitations and the possible solution in the existing technology for 6G network

Technologies	Citation	Possible solutions
DDPG	[16]	The performance losses will be mitigated by involving the quantization-aware training algorithm to manage the spectral efficiency.
Fly-IRS assisted 6G THz	[17]	It is necessary to optimize the UAV trajectory to minimize the total UAV flying time.
CNN-LSTM	[18]	The optimization for the channel estimation needs to be involved to enhance the performance and minimize the complexity.
Neural network	[19]	The complexity of managing the RIS-enabled system is addressed by involving the ground-breaking DNN models.
LSTM-MADRL	[20]	The computational burden has been alleviated by transitioning the individual resource blocks to group utilization.
Autoencoder	[21]	The proposed solution has been enhanced by involving federated learning along with the collaborative detection of distributed attacks for different base stations.
Neural network	[22]	The prediction result has improved by the estimation of the terminal-side user location and positional parameters.
WPPFL-RS	[23]	The scalability and adaptability have been enhanced by optimizing the aggregation model for the huge network.
DT	[24]	It is recommended to focus on implementing the generative AI-based diffusion model to solve the difficulties.
Clustering algorithm	[25]	It is important to initiate the hierarchical clustering for the high-dimensional data.
MARL-GNN	[26]	The issues in the energy transmission and UAV-based data collection for the wireless network were investigated along with the optimization of energy consumption.
NNAGbRD-V2V-SLM	[27]	The reliable and adaptable resource allocation required for the different 6G V2X scenarios.
Supervised regression machine learning	[28]	The deep learning model will be used to forecast various parameters to improve the results.
ADN and NFV	[29]	Resource management is necessary for secure and scalable wireless communication.
Machine learning	[30]	Fine-tuning is required to achieve better results.

5. Summary

This work provided a comprehensive review of the future 6G wireless communication network. The framework covered the construction and key performance of the 6G network. The significant technologies utilized for the enhanced performance were examined in detail. The operation principle of each technology and its fundamental advancement were also described. Further highlighted the existing state-of-the-art model along with its challenges. Overall, the

work offers a clear vision of 6G, which was significant for both academic and industrial research.

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