Intelligent 6G Wireless Network with Multi-Dimensional Information Perception

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DOI: 10.12142/ZTECOM.202302002

https://kns.cnki.net/kcms/detail/34.1294.TN.20230516.1739.006.html, published online May 17, 2023

Manuscript received: 2023-03-15

Abstract: Intelligence and perception are two operative technologies in 6G scenarios. The intelligent wireless network and information perception require a deep fusion of artificial intelligence (AI) and wireless communications in 6G systems. Therefore, fusion is becoming a typical feature and key challenge of 6G wireless communication systems. In this paper, we focus on the critical issues and propose three application scenarios in 6G wireless systems. Specifically, we first discuss the fusion of AI and 6G networks for the enhancement of 5G-advanced technology and future wireless communication systems. Then, we introduce the wireless AI technology architecture with 6G multi-dimensional information perception, which includes the physical layer technology of multi-dimensional feature information perception, full spectrum fusion technology, and intelligent wireless resource management. The discussion of key technologies for intelligent 6G wireless network networks is expected to provide a guideline for future research.

Keywords: 6G wireless network; artificial intelligence; multi-dimensional information perception; full spectrum fusion

Citation (Format 1): YANG B, LIANG X, LIU S N, et al. Intelligent 6G wireless network with multi-dimensional information perception [J]. ZTE Communications, 2023, 21(2): 3–10. DOI: 10.12142/ZTECOM.202302002

Citation (Format 2): B. Yang, X. Liang, S. N. Liu, et al., "Intelligent 6G wireless network with multi-dimensional information perception," *ZTE Communications*, vol. 21, no. 2, pp. 3–10, Jun. 2023. doi: 10.12142/ZTECOM.202302002.

1 Introduction

From the perspective of 6G vision and requirements, there are several typical application scenarios, including smart cities, intelligent transportation, industrial intelligence, immersive Extended Reality (XR), holographic communication, sensory interconnection, and integrated perception and communications[1–7]. Intelligence and perception have become two keywords in 6G scenario applications[8–15]. Therefore, fusion is becoming a typical feature and a key challenge that distinguishes 6G from previous generations of communication systems.

Studies on the spectrum are essential for mobile communication systems. In the future, the 6G spectrum will expand to frequency bands with more abundant spectrum resources, e.g., terahertz and visible light. Larger bandwidth, higher frequency and full spectrum technology become the trend of evolution. Millimeter wave technology has been supported in the 5G wireless communication system standards. In the 6G era, millimeter wave technology will be mature and widely used. At the same time, the exploration of the terahertz band becomes a popular topic of research on 6G[1–3, 13–15].

For the full spectrum of 6G, we think the coverage of medium and low-frequency bands should be mainly guaranteed. Millimeter waves and terahertz provide a large bandwidth to form a multi-frequency collaborative ubiquitous networking pattern. Operators will face more fragmented spectrum resources. In order to improve the efficiency of resource utilization and network operation management, these fragmented spectrum resources must be fused. For example, 6G full spectrum fusion can be achieved by designing architecture and a series of key technologies.

2 Key Issues and Scenarios in 6G

Based on the aforementioned vision of 6G and the trend of spectrum fusion, we introduce some perspectives on the design of native intelligence systems for 6G. Intelligence, as a key capability of wireless communication networks, is becoming an enabling technology for emerging businesses. From 5G to 6G, artificial intelligence (AI) will complete the role transformation from assistance to endogeny. The fundamental design principle of wireless AI is to create a future high-efficiency and sustainable network. We need to efficiently utilize the fragmented spectrum and improve energy efficiency.

Therefore, we introduce three key scenarios in 6G for the fusion of AI and networks:

1) Scenario 1: assisting the enhancement of 5G-advanced

technology to improve network efficiency

This scenario mainly includes the existing network architecture based on 5G evolution, defining the wireless AI technology framework, mechanisms and signaling processes to achieve the integration of traditional technologies and AI, boost the technology enhancement of 5G evolution, and improve the efficiency of networks and system performance. Currently, the initial research work on intelligent air interface is underway in 3GPP Release 18. It lays the groundwork for the evolution of 5G systems and the design of 6G systems.

2) Scenario 2: AI native enabling typical high-value applications

Emerging 6G businesses, such as metaverse, immersive XR, digital twins and fully automated driving, will pose high requirements for future wireless communication systems. An AI native wireless network in 6G will become a key enabling technology for high-value application scenarios to meet the demands of high-value application scenario users for the ultimate experience and ultra-high network operational efficiency.

3) Scenario 3: AI native building efficient and sustainable networks for operators

With the goal of full spectrum fusion in 6G, AI native wireless networks will address the super-high complexity and challenges of network management and operation brought about by multi-dimensional network deployment in future mobile communication systems. AI native will be used to realize resource awareness and dynamic control of 6G wireless networks with multiple operators, multiple frequency bands and multiple modes, improving network energy efficiency and resource utilization efficiency and building a green, efficient and sustainable 6G network.

3 Wireless AI Technology Architecture

Therefore, we design and propose a 6G wireless AI architecture for multi-dimensional information perception, which consists of three aspects: physical layer technology for multi-dimensional feature information perception, intelligent full-spectrum fusion, and intelligent wireless resource management.

Achieving the deep integration between AI and wireless communications requires the support of big data of wireless communications, which enables AI to perceive, extract and integrate multi-dimensional information to solve problems with high complexity. Data is the essential requirement of the design of wireless communication systems with internal AI. Facing the multi-objective optimization problems, future wireless AI will be based on multi-dimensional information perception, e.g., scene information, service information, network state information, terminal measurement information, and so on.

In addition, the current design of the wireless protocol stack and the demand for multi-dimensional information perception from the bottom to the top are contradictory. Therefore, when designing the 6G protocol stack, we need to consider matching the requirements of multi-dimensional information perception for wireless AI. In this section, we introduce the design from three aspects in detail.

3.1 Multi-Dimensional Feature Information Perception

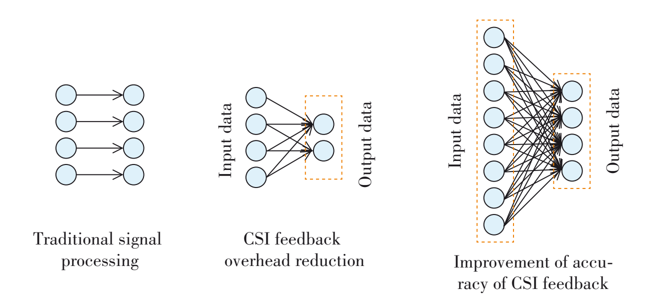
We consider the physical layer technology of multi-dimensional feature information perception to be achieved through AI-driven feature extraction, perception, and fusion of multi-dimensional wireless data (e. g., channel impulse response, received signal power, and so on) in the frequency, time, space, or angle domain. This physical layer technology of multi-dimensional feature information perception includes AI-driven extra large-scale massive multiple-input multiple-output (XL-MIMO) technology and AI-enabled localization technology.

3.1.1 AI-Driven XL-MIMO Technology

AI-based XL-MIMO technology, such as intelligent channel state information (CSI) enhancement and intelligent beam management, can integrate with some traditional functions through AI, achieving the replacement of certain functional modules and helping to improve the utilization efficiency of network resources and system performance.

Different from the codebook-based CSI acquisition method in traditional wireless communication systems, intelligent CSI enhancement technology includes intelligent CSI compression feedback and intelligent CSI prediction. Intelligent CSI feedback enhancement can increase the number of reference signals used for obtaining channel state information. As shown in Fig. 1, AI technology is used to compress and reconstruct the multi-dimensional channel feature information of CSI feedback, reducing the overhead of air interface CSI feedback or improving CSI reconstruction accuracy.

Intelligent CSI feedback technology usually deploys an AI model at both the base station (BS) side and the user equipment (UE) side, including CSI compression and CSI reconstruction. During the stage of training an AI model, the UE estimates multi-dimensional channel feature information based on reference signals and feeds the multi-dimensional channel feature information back to the BS as input and label data for



▲Figure 1. Enhancement of artificial intelligence (AI)-based CSI feedback the training of the AI model. During the inference stage of the AI model, the UE sends the estimated channel feature vector to the encoder for CSI compression. Then, the compressed CSI codeword is reported to the BS. The BS uses the decoder to reconstruct the channel feature vector from the codeword that is fed back. The channel feature vector is used for precoding. We propose to utilize AI techniques to extract CSI features in a fully efficient manner, with lower inference complexity but comparable performance to traditional codebook methods. With the application of intelligent CSI feedback technology in dense urban areas and other scenarios, we estimate that more than 60% of uplink feedback overhead can be saved[16]. In addition, further improvement in compression performance can be achieved through intelligent retraining and optimization of quantization modules of AI models.

In traditional methods, time delay exists among CSI measurement, feedback and precoding, which results in a system performance loss since the current wireless channel uses an outdated CSI. This problem is more pronounced in high-speed mobility scenarios. As shown in Fig. 2, intelligent CSI prediction technology can utilize channel correlation features in the time domain to predict future CSI based on AI algorithms. In addition, CSI prediction technology can be enhanced by exploiting multi-dimensional channel feature information such as multi-user and bidirectional channel reciprocity. The traditional codebook information and uplink reference signal measurement results are used as inputs to extract and fuse features through AI algorithms for CSI prediction, thereby improving the accuracy of CSI prediction.

The intelligent CSI enhancement technology that perceives multi-dimensional feature information has broad application prospects and is of great significance for improving network performance and resource utilization efficiency.

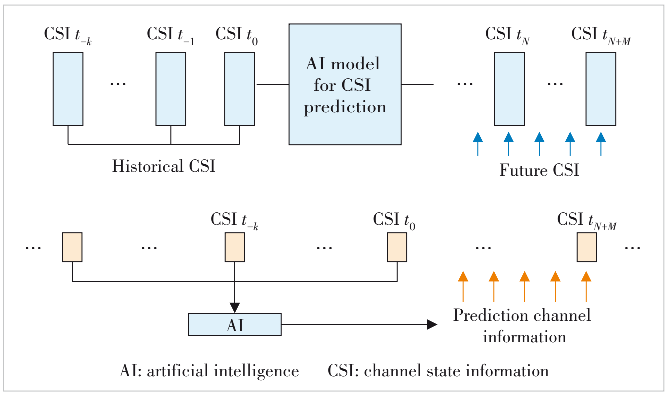
The widespread use of massive antenna arrays poses great challenges to future beam management. As shown in Fig. 3, intelligent beam management can use AI algorithms to predict beams in the spatial and temporal domains, reduce beam measurement pilot overhead and measurement latency, and significantly improve beam management accuracy and system performance. Fig. 3(a) illustrates our proposition that implements AI algorithms to solve the conventional beam management problem through a classification model at high frequency, which can significantly reduce the required number of beam directions for measurement. Specifically, instead of measuring 32 BS beam directions and eight UE beam directions as in traditional methods, measuring only eight and four beam directions for the BS and UE respectively is sufficient. This reduction in measurement time by 87.5% results in an improved beam prediction accuracy of more than 45%[17]. Therefore, AI-based beam management can provide new ideas for defining mechanisms for future ultra-high frequency XL-MIMO beam management, simplifying relevant signaling processes while providing excellent prediction performance.

3.1.2 AI-Enabled Precision Positioning Technology

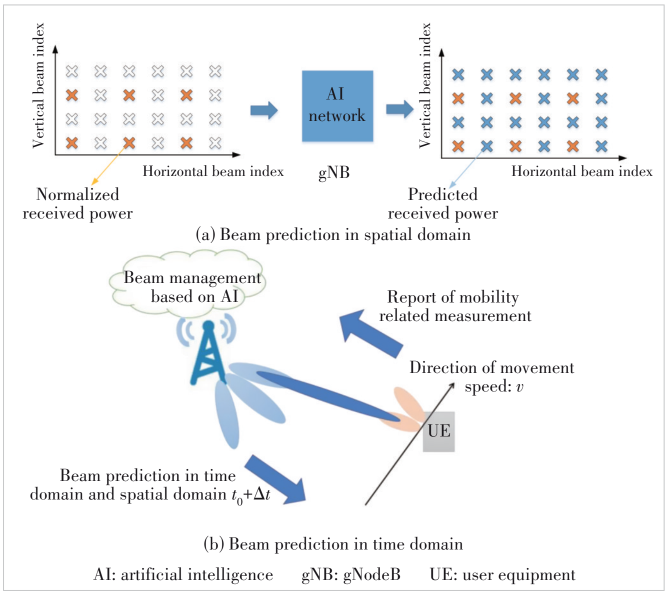
Traditional positioning technology mainly solves the problem of indoor positioning, and its main idea is to calculate the position of a user based on the measurement of multiple station points, especially the line-of-sight (LOS) path. Common methods include the time of arrival (TOA), time difference of arrival (TDOA), multi-round trip time (Multi-RTT), and so on.

The introduction of AI technology is mainly used to solve the impact of non-line-of-sight (NLOS) paths on positioning calculation and the problem of inaccurate positioning in heavy NLOS environments. By utilizing AI to extract multi-dimensional feature information of measurement signals and conduct binary classification for LOS and NLOS paths, the interference of NLOS path information on positioning calculation can be mitigated. The CSI with higher LOS probability is used to calculate the UE position, which can improve positioning performance, especially when there are few indoor antennas to improve positioning accuracy.

In scenarios with heavy NLOS, traditional positioning algorithms are no longer applicable because the measurement sig-



▲**Figure 2. AI-based CSI prediction**



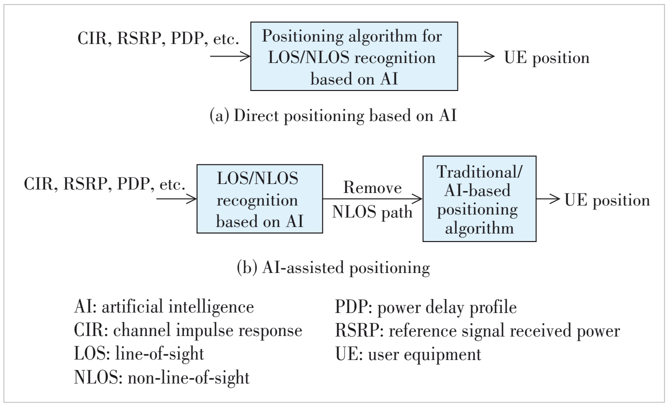
▲**Figure 3. Intelligent beam management** nals between the UE and BS have few LOS paths. AI algorithms can learn the mapping between multi-dimensional feature information and location information. We propose that in heavy NLOS indoor factory scenarios, using AI algorithms to extract and fuse multi-dimensional measurement signal features such as channel impulse response (CIR), TOA and reference signal received power (RSRP) can improve the positioning accuracy from 10 meters to decimeter level.[18]

As shown in Fig. 4, there are two ways to integrate AI with positioning technology. One is to input multi-dimensional information such as CSI, reference signal received power, and delay power spectral estimation value into the AI model, and extract and fuse features through the model to directly output the final positioning coordinates. The other method is to combine AI with traditional positioning algorithms, which is used to identify and optimize the input information of traditional positioning algorithms, thereby improving positioning accuracy.

AI models can practically be deployed in the location management function (LMF), the BS side, or the UE side for assisted positioning. When an AI model is deployed in the LMF as an input node, the BS and UE need to provide feedback on the required measurement positioning information, which introduces additional delay and overhead due to the large feedback overhead. When the AI model is deployed at the BS or UE side, the deployed node can, based on AI, select location-related measurement information from some paths with high LOS probability or optimized positioning measurement information and feedback it to the LMF. The LMF generates the accurate position coordinates of the UE, which reduces the delay and feedback overhead. As the BS and UE need to collect data for model training, the intelligent positioning enhancement technology at the BS side has a more important value of research, considering that UE has relatively weaker computing and storage resources and the mobility problem of UE will lead to the storage of a large amount of model information.

3.2 Intelligent Full Spectrum Fusion Architecture

6G full spectrum fusion will expand and improve the dimension and complexity of wireless network management. AI native can achieve intelligent full spectrum fusion for multi-tasking, solve the spectrum fragmentation problem faced by operators, and create efficient and sustainable networks.



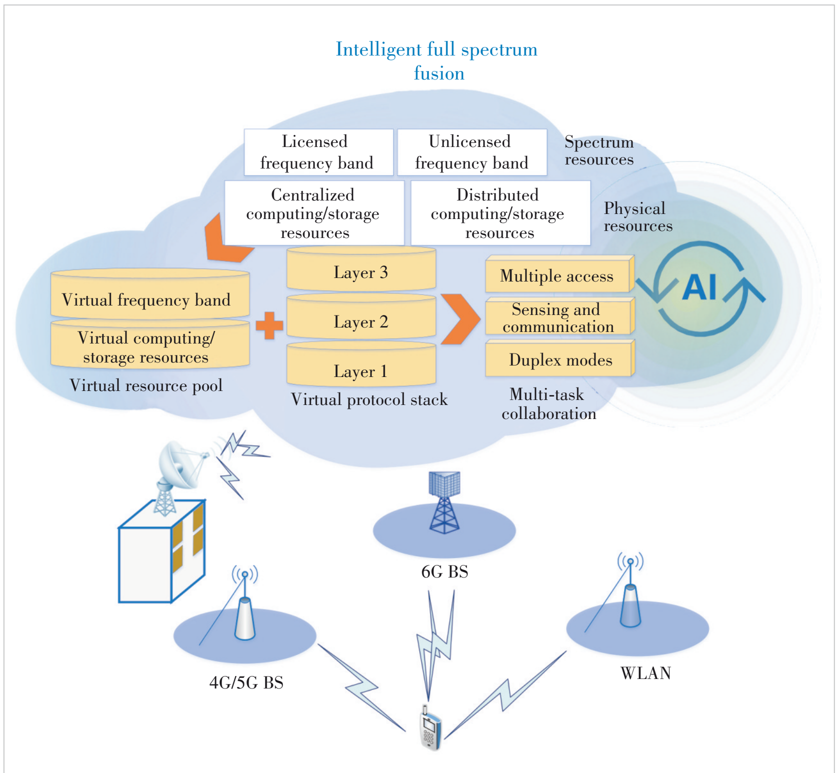
▲**Figure 4. AI-based precision positioning technology**

In terms of architecture design, the basic principles are to achieve layered and distributed decomposition of complex problems through multi-level architecture. One is to virtualize physical resources such as spectrum resources, computing and storage resources through centralized and distributed computing and storage resources, and to face 6G different scenes and business needs; unified resource packaging is achieved through intelligent control methods to form virtual resource units and achieve full spectrum virtual resource fusion. The second point is to enable intelligent and flexible loading of the virtual protocol stack through AI native and shield the differences in multi-tasking in the protocol stack, frame structure and other aspects; in this way full spectrum protocol stack fusion will be achieved and channels between various protocol stack layers will be opened to achieve cross-layer optimization. The third point is to enable multi-task collaboration through AI native, to effectively integrate multi-level computing, communication, and storage resources through cloud-network-edge-terminal deep fusion, using a unified resource model and service-oriented distributed architecture, and to achieve intelligent collaborative networking of multiple frequency bands, multiple systems and multiple operators.

Intelligent full spectrum fusion can specifically include multi-access fusion, communication and sensing fusion, and fusion of multiple duplex modes. In actual network operation and management, the optimization goals of multi-spectrum fusion are multi-dimensional. The network needs to carry out multi-task collaboration to avoid strategy conflicts caused by individual decisions, thus realizing the intelligent full spectrum fusion mechanism of future 6G networks. Multi-task driven intelligent full spectrum fusion ultimately virtualizes physical resources into cloud-based resource pools, as shown in Fig. 5. Targeting various scenarios and business requirements of 6G, resources are packaged and formed into virtual space, time, frequency, and computing resource units for user allocation through intelligent regulation. Through the intelligent and flexible loading of AI native enabled virtual protocol stack, the fusion of the full spectrum protocol stack is achieved.

3.2.1 Intelligent Multi-Access Fusion

The current status of mobile communications is characterized by the coexistence of multiple generations of communication standards. It can be predicted that in the future, networks will be in a long-term situation of coexistence of 4G, 5G and 6G multi-frequency bands and multi-access standards. Emerging services pose greater challenges to the network in terms of transmission rate, delay, reliability, security, and so on. Based on the machine learning (ML) framework and utilizing various AI learning algorithms such as federated learning and rein-



▲**Figure 5. Multi-task driven intelligent full spectrum fusion**

forcement learning, intelligent multi-access technology maximizes the network capacity in terms of coverage, capacity, energy efficiency and other aspects by integrating the advantages of multi-frequency bands and multi-standard networks through AI native, which improves the operational efficiency of the network.

For future business scenarios, multi-access convergence is mainly reflected in the need for AI-native solutions to the following fusion requirements:

1) With the scarcity of low-frequency wireless resources, the 6G frequency band will extend to significantly higher frequencies than 4G and 5G networks, forming a multi-frequency collaborative networking scenario. High frequencies have the advantage of large bandwidth and high transmission rates, but suffer from poor coverage due to path loss and penetration loss. Intelligent multi-frequency collaborative networking can be achieved by fusing the 6G high-frequency band with the 4G/5G network frequency band, providing both wide-area coverage and high transmission rates.

2) 6G networks and wireless local area networks (WLAN) can be intelligently integrated for indoor environments and vertical industries. When 6G and WLAN are fused at the access network level, WLAN will access the 6G base station at the wireless access network side to obtain business flows and forward them to terminals. AI-driven intelligent multi-access collaborative technology can achieve load and environment awareness for multi-access networks, enabling intelligent flow distribution for 6G and WLAN business flows.

Finally, multi-connection of 6G+5G/4G+WLAN can achieve the fusion of advantages of all network standards. Intelligent network architecture design and AI algorithm solutions that combine centralized and distributed control are urgently needed for wireless resource management and dynamic adjustment between multiple standards to meet the requirements of future 6G businesses.

3.2.2 Intelligent Fusion of Communication and Sensing

With the development of the fusion of communication and sensing towards 6G full spectrum, intelligent wireless air interfaces will achieve multi-dimensional feature information extraction, sensing, and fusion of multiple communication signals, communication and sensing signals and multiple sensing signals. The full spectrum fusion technology for AI native and sensing will realize the mutual promotion and fusion development of intelligence and sensing, and further enhance the physical layer of 6G wireless networks and wireless resource management technology. In practical applications, AI-based positioning technology will be limited by the wireless datasets obtained by traditional communication signals. Towards 6G, emerging services such as immersive XR, metaverse and holographic communication will require higher precision positioning. Extending to the 6G full spectrum, the collaborative and accurate multi-frequency perception positioning with fusion sensing signals will greatly improve positioning accuracy and significantly promote the development of future 6G intelligent factories, autonomous driving, smart homes and other applications with wireless AI big data.

3.2.3 Intelligent Fusion of Duplex Modes

With the fusion of various intelligent wireless duplex modes, future networks may support the coexistence of multiple duplexing modes, such as traditional duplexing, flexible duplexing and full duplexing. In multi-frequency cooperative scenarios, CSI, beam direction information and terminal trajectory information working in multi-frequency, same-frequency and adjacent-frequency bands have explicit or implicit correlations. AI-driven XL-MIMO technology may use multi-frequency cooperative networking and flexible duplexing fusion mechanisms to obtain higher-dimensional feature information, further enabling AI-driven improvements in network resource utilization efficiency and system performance. In terms of intelligent CSI acquisition and intelligent beam management, intelligent pooling of multi-frequency and large bandwidth resources can be fully utilized for resource allocation and variable-rate AI model architecture. This fusion of multi-dimensional information such as geographic location and user orientation can meet intelligent high precision, high efficiency, and low-power consumption requirements of future XL-MIMO technology.

3.3 Intelligent Radio Resource Management

In 6G systems, AI native will become an engine for wireless networks to achieve self-learning, self-operation, self-maintenance and self-evolution. By leveraging multi-task collaborative optimization and intelligent ubiquitous multi-level network resource coordination, intelligent wireless resource management can be enabled, and deep perception of user scenarios and collaborative optimization of network services can be achieved, effectively enhancing wireless system performance and fully ensuring user service experience. To achieve intelligent wireless resource management, a multi-level architecture design is required to build a self-intelligent wireless network, which mainly includes the following three aspects:

1) Intelligent multi-level network resource collaborative management

AI technology enables 6G wireless networks, which can timely perceive user needs through real-time data collection and analysis, activate services on demand and carry out multi-objective joint optimization to promote the network, to achieve the best balance between system energy consumption and performance. The deep fusion of AI technology and 6G wireless networks includes the following several key points:

• Establishing an efficient data knowledge graph, designing a universal database storage model, preprocessing the collected data by classification, establishing a dataset sharing mechanism, fully mining the features in the data, and achieving the accurate perception of user needs;

• Implementing multi-scenario and multi-task collaborative optimization, which integrates and fully utilizes the data and computing resources in the network and effectively avoids duplicate data training and maximizes system performance;

• Constructing an AI model repository to improve the robustness and generalization of AI models, providing technical support for diversified network optimization services, and assisting the network in achieving self-optimization and self-evolution.

2) Network optimization with multi-task collaboration

By deeply integrating 6G wireless networks with AI technology and based on big data in wireless networks, the optimization problems in such areas as mobility management, network energy conservation and service offloading can be effectively solved. With the collection and management of global network data, AI algorithms can process and train user measurement information, network configuration parameters, service requirements and traffic, as well as external environmental input information to accurately predict user movement trajectories and traffic of the BS. This can recommend more reasonable network configurations and strategies to effectively ensure the continuity of user services in the network, while reducing the energy consumption of the BS and lowering energy costs of the operator. Adaptive and predictive AI and ML algorithms can help networks establish autonomy, break through traditional technical barriers, and create high-quality intelligent 6G applications[19].

As the mobile network is composed of various overlapping network services, all service characteristics and goals need to be considered. Taking wireless network optimization as an example, the optimization goals in actual networks are multi-dimensional, so network optimization requires multi-task collaboration to avoid configuration conflicts caused by separate decisions and achieve the global optimization of the wireless communication system, thereby satisfying user needs for extreme differentiation and high-quality service experience.

3) Deep-aware network service collaborative optimization

Intelligent wireless resource management will be based on multi-dimensional information of AI native scenarios and businesses, network capability openness and native perception capability of the network to enable the collaborative optimization of the network and businesses[20]. This will realize the intelligent wireless network slicing resource management, mobility management and network energy saving.

Network slicing is a key technology for operators to support on-demand networking and resource scheduling for both business-to-business and business-to-customer services. In order to provide extremely differentiated end-to-end service quality assurance for 6G, AI-driven intelligent wireless resource management will break down the barriers between services and wireless network perception. We suggest that intelligent resource scheduling can be used to optimize wireless slice resource allocation based on the reinforcement learning framework and through learning, perception and prediction of dynamic wireless environments, application scenarios, and multi-dimensional user business information. This may significantly improve network resource utilization efficiency and ensure service experience for different priority businesses[21–23]. In addition, lightweight and distributed intelligent slice resource management utilizing algorithms such as small sample learning, transfer learning, federated learning and collective learning is an important research direction for the future, for the sake of user behavior and business privacy, information security, and distributed deployment of computing and storage resources in the network.

6G networks have higher dynamism, multi-layering and dimensionality, which leads to more frequent inter-cell handovers, posing huge challenges to 6G network mobility management. On the one hand, a cell-free network architecture design can be used to reduce the frequent interaction of inter-cell handover signaling. On the other hand, with the AI native capabilities of the network, intelligent mobile trajectory prediction can be achieved for terminals, deducing the optimal intercell handover scheme and thereby ensuring communication connectivity and dynamic load balancing of the network. AI can use deep reinforcement learning to solve complex decision-making problems and optimize inter-cell handover strategies in real time, minimizing transmission latency and ensuring reliable wireless connections. In the future, in large-scale vehicle-to-vehicle communication scenarios of fully autonomous driving, 6G networks need to meet the high-speed mobility and latency-sensitive requirements of vehicles. AI technology can learn user behavior, such as scenes and vehicles, through deep learning and long short-term memory (LSTM) networks, predict the future motion state and trajectory of a period of time, and effectively avoid frequent handovers and handover failures[24].

The introduction of 6G millimeter-wave and terahertz multi-frequency and high-bandwidth will increase network operation energy consumption and carbon emissions. With the increase in ultra-high-frequency BS coverage density and the diversity of business requirements of the UE, the tidal phenomenon of 6G communication demands will become more prominent, leading to large energy consumption for the network when BSs are in low-traffic periods in the ultra-dense networking scenarios. Therefore, multi-dimensional scene and business information perception at the BS side is necessary to achieve adaptive adjustment of wireless network scene businesses. Through deep learning and LSTM based on the spatiotemporal correlation of historical demands of the BS, the future business and traffic can be predicted[25], and a reinforcement learning network can be used to design semi-static or dynamic BS switch-off energy-saving states. Through a dynamic balance between the user business guarantee and network energy-saving multi-BS collaborative intelligent networking strategy, overall network energy consumption can be reduced.

4 Conclusions

In this paper, we propose a wireless AI technology architecture with multi-dimensional information perception to solve the key challenge to developing AI native 6G systems, which includes multi-dimensional feature information perception technology in the physical layer, intelligent full spectrum fusion technology, and intelligent wireless resource management.

At present, ongoing studies in 3GPP focus on integrating AI/ML with traditional physical layer techniques and radio access network level signaling enhancement. This paper provides our thoughts and a guideline on the roadmap of the evolution of 5G-Advanced to the intelligent 6G wireless network. The time left to study and clarify the integration of AI/ML with B5G or design an AI-native 6G RAN is limited. Researching the proposed intelligent radio resource management and intelligent full spectrum fusion technology such as distributed learning-based technologies and AI/ML-based mobility enhancement is crucial for better preparation for 6G. Relevant research results show that AI and ML are powerful tools for improving the performance of existing or future wireless communication systems. It will be exciting to see the development of 6G wireless systems in the coming years, which will be built upon the foundation of the proposed application scenarios and wireless AI technology architecture.

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