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Research on the Integrated 6G Communication, Sensing, and Computing Network Architecture and Key Technologies

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Abstract: The integration of communication, sensing, and computing in 6G represents a significant exploratory direction for the future of the communication field. This paper delves into the network architecture and key technologies of 6G integrated communication, sensing, and computing. With the deepening application of 5G networks, 6G, as the future development direction of communication technology, will integrate technologies such as artificial intelligence and big data to achieve higher speeds, lower latency, broader coverage, and stronger intelligent processing capabilities. The 6G integrated communication, sensing, and computing network architecture is divided into four layers: sensing, communication, computing, and application, offering advantages such as efficient information exchange, powerful computing capabilities, flexible network configuration, and a wide range of application scenarios. Key technologies include communication-sensing integration, computing power network technology, and intelligent resource allocation. These technologies will drive the digital transformation and intelligent development of various industries, creating greater value for society.

Keywords: 6G; integrated communication, sensing, and computing; network architecture; key technologies

Introduction

With the widespread deployment of 5G networks globally and the rise of high-precision sensing algorithms and artificial intelligence (AI), communication technology is entering a new stage of development. To meet the escalating application demands, such as ultra-high-definition video transmission, autonomous driving, and remote healthcare, research on 6G networks has emerged. The 6G integrated communication, sensing, and computing network architecture, as a crucial direction for future communication technology, aims to deliver communication services with higher speeds, lower latency, and broader coverage by deeply integrating sensing, communication, and computing capabilities. This paper will provide a detailed exploration of the design, functions, and advantages of the 6G integrated communication, sensing, and computing network architecture. It will also analyze key technologies such as communication-sensing integration, computing power networks, and intelligent resource allocation, offering theoretical support and practical guidance for the digital transformation of the future intelligent society.

1. Background of 6G Network Development

With the widespread deployment and deep application of 5G networks globally, the field of communication technology has ushered in new developmental opportunities. The demand for communication networks continues to rise and evolve. In terms of data transmission, although 5G has achieved high-speed transmission, emerging application scenarios such as real-time ultra-high-definition video transmission and large-scale rapid data exchange demand even more extreme speeds. Regarding network latency, scenarios with stringent real-time requirements, such as autonomous driving and remote healthcare, necessitate lower latency to ensure operational accuracy and safety, a level that current 5G latency struggles to fully meet. In terms of coverage, communication needs in remote areas, underground spaces, and other special environments remain inadequately addressed by 5G networks, highlighting the urgent need for further expansion. As for intelligent processing capabilities, with the explosive growth of Internet of Things (IoT) devices, massive amounts of data require efficient and intelligent processing and analysis, areas where 5G networks still have room for improvement in both depth and breadth.

Against this backdrop, 6G networks, as a critical direction for the future of communication technology, will deeply integrate a variety of advanced technologies such as artificial intelligence, big data, and blockchain. Leveraging this technological convergence, 6G networks will not only achieve goals of higher speeds, lower latency, and broader coverage compared to 5G

but will also possess enhanced intelligent processing capabilities [1]. This will enable 6G to meet the diverse application needs of the future. For instance, the real-time high-definition rendering of characters and scenes in holographic communication, seamless and intelligent interactions between vehicles and infrastructure in intelligent transportation systems, and efficient collaboration and intelligent production control among devices in industrial Internet environments will all rely on the powerful performance of 6G networks. 6G will provide robust support for societal digital transformation, driving industries toward deeper levels of intelligence and digitization.

2. Integrated 6G Communication, Sensing, and Computing Network Architecture

2.1 Overall Architecture Design

The integrated 6G communication, sensing, and computing network architecture adopts a layered design philosophy, which is divided into four layers: the sensing layer, the communication layer, the computing layer, and the application layer, as illustrated in **Figure 1**. The sensing layer is responsible for collecting environmental information and user status data, utilizing various sensors to perceive the physical world. The communication layer handles the transmission and exchange of information, employing novel communication technologies and protocols to ensure efficient and reliable data transfer. The computing layer processes and analyzes the sensed and communicated data, providing robust computational capabilities. Finally, the application layer caters to various specific use cases, offering users a wide range of services.
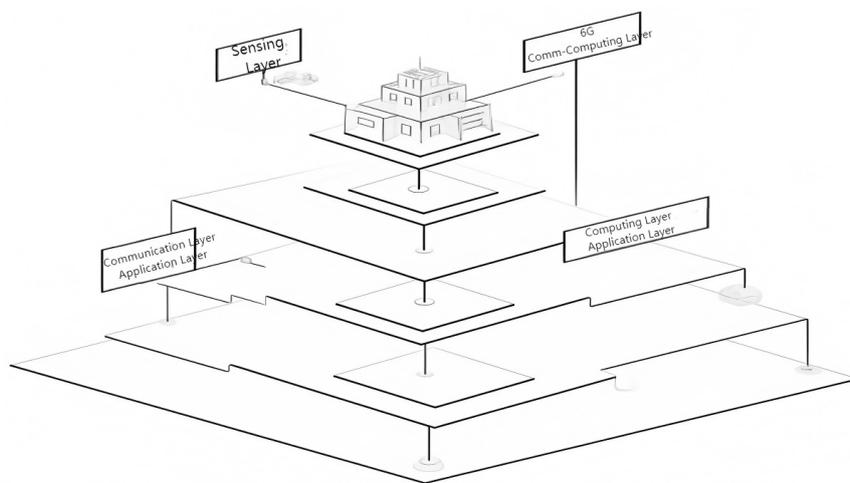

Figure 1. 6G Integrated Communication, Sensing, and Computing Network Architecture Diagram

2.2 Functions and Composition of Each Layer

(1) Sensing Layer

The sensing layer consists of various types of sensors, including environmental sensors, location sensors, and biosensors. These sensors can collect real-time information about the surrounding environment and user status, converting this information into electrical or digital signals to provide foundational data for subsequent processing and analysis [2].

(2) Communication Layer

The communication layer is one of the core layers of the 6G integrated communication, sensing, and computing network. It is responsible for transmitting the information collected by the sensing layer to the computing layer and feeding the processed results from the computing layer back to the application layer. The communication layer employs novel Reconfigurable Intelligent Surface (RIS) communication technology. Leveraging its high-performance electromagnetic wavefront manipulation capabilities, precise control of key electromagnetic response parameters such as amplitude, phase, and polarization of each unit in the array, and the implementation of beamforming and channel reconstruction through signal processing algorithms, it significantly enhances the capacity and signal quality of wireless communication systems in dynamic environments, such as multi-user mobility and complex electromagnetic interference scenarios [3].

(3) Computing Layer

The computing layer provides robust computational support for the 6G integrated communication, sensing, and computing network. It includes edge computing nodes and cloud computing centers. Edge computing nodes, located close to users and data sources, can quickly process sensing information and communication data, reducing latency. The cloud computing center, equipped with powerful computing resources and storage capabilities, aggregates sensing data from edge computing nodes to perform in-depth analysis and processing of large-scale sensing data. By extracting key features and filtering out redundant or irrelevant factors, it effectively achieves comprehensive global network awareness.

(4) Application Layer

The application layer serves various specific application scenarios, providing users with diverse services. Application scenarios include intelligent transportation, smart healthcare, industrial internet, holographic communication, and more. Through collaboration with the sensing, communication, and computing layers, the application layer enables intelligent perception, decision-making, and control of application scenarios. For example, in an intelligent transportation scenario, the application layer can transmit traffic flow information and vehicle location data collected by the sensing layer to the computing layer via the communication layer for processing and analysis. Based on the analysis results, it can then intelligently control traffic signals to optimize traffic scheduling.

2.3 Analysis of Architectural Advantages

First, efficient information interaction. The integrated communication, sensing, and computing network architecture breaks down the traditional boundaries between communication, sensing, and computing, enabling seamless information exchange and sharing [4]. Information collected by the sensing layer can be quickly transmitted to the computing layer for processing, and the results from the computing layer can be promptly fed back to the application layer, improving information utilization efficiency and response speed. Second, powerful computing capabilities. Through the collaboration of edge computing and cloud computing, the integrated communication, sensing, and computing network architecture provides robust computational support. Edge computing nodes can quickly address local computing demands, while cloud computing centers can perform in-depth analysis and processing of large-scale data, meeting the computing requirements of various application scenarios. Third, flexible network configuration. By adopting technologies such as Software-Defined Networking (SDN) and Network Function Virtualization (NFV), the integrated communication, sensing, and computing network architecture enables flexible network configuration and efficient management. Network administrators can dynamically allocate and adjust network resources based on actual needs, improving network utilization and performance. Fourth, broad application scenarios. The integrated communication, sensing, and computing network architecture supports a wide range of application scenarios. Through deep integration with various industries, it can drive digital transformation

and intelligent development across sectors, creating greater value for society.

3. Key Technologies for 6G Integrated Communication, Sensing, and Computing

3.1 Communication-Sensing Integration Technology

Communication-sensing signal processing technology, as a core element of communication-sensing integration, primarily focuses on how to effectively process and deeply integrate communication signals and sensing signals. In communication signal processing, the application of advanced technologies such as modulation and demodulation, channel coding, and signal detection can significantly enhance communication reliability and anti-interference capabilities. For sensing signal processing, techniques such as filtering, feature extraction, and target recognition are employed to accurately extract valuable information from the sensing signals. Furthermore, it is essential to delve into joint processing methods for communication and sensing signals to achieve synergistic operation of communication and sensing functions. For instance, by adopting joint beamforming technology to optimize the design of communication beams and sensing beams, the overall performance of both communication and sensing can be improved. Concurrently, as the volume of communication and sensing services continues to rise, spectrum resources are becoming increasingly scarce, giving rise to communication-sensing spectrum sharing technology. This technology enables the sharing of spectrum resources between communication and sensing services, effectively improving spectrum utilization efficiency [5]. It primarily encompasses dynamic spectrum allocation and cognitive radio technologies. Dynamic spectrum allocation technology dynamically allocates spectrum resources based on the actual demands of communication and sensing services, achieving efficient utilization of spectrum resources. Cognitive radio technology, on the other hand, perceives the surrounding spectrum environment and automatically adjusts communication parameters to avoid interference with other services, thereby facilitating the sharing of spectrum resources.

3.2 Computing Power Network Technologies

First, computing power perception and measurement technologies. These technologies form the foundation of computing power networks. They enable real-time perception of the status of computing resources within the network and allow accurate measurement of those resources. Computing power perception technology collects information on the computing capabilities of each node by deploying perception nodes throughout the network. Computing power measurement technology, in turn, adopts unified measurement standards to quantitatively evaluate computing resources, providing a basis for resource allocation and scheduling. For example, a computing power index can be used to measure the capability of a node—the higher the index, the stronger the node's computing capacity. Second, computing power scheduling and allocation technologies. These technologies allocate computing resources to users in a rational manner based on user demands and the current state of computing resources in the network. The core objective is to achieve optimal allocation of computing resources and minimize total task processing latency through intelligent algorithms, such as genetic algorithms and particle swarm optimization algorithms.

Taking an edge computing scenario as an example, suppose there are η tasks to be processed and γ edge computing nodes. The data size of task i is D_i (in GB), the computing capacity of node j is c_j (in GB/s, i.e., the amount of data that can be processed per second), and the transmission rate from task i to node j is R_j (in GB/s). The total processing latency T_j for assigning task i to node j can be expressed as:

$$T_v = \frac{D_i}{R_g} + \frac{D_j}{C_j}$$

Using this formula, the latency of different task–node allocation combinations can be calculated. Intelligent algorithms can then be applied to select the allocation scheme with the minimum total latency. In practical applications, the transmission rate R_j can be determined based on the user's location (the shorter the distance, the higher the rate), while the computing capacity c_j is determined by the node's hardware configuration. Ultimately, tasks are assigned to edge computing nodes that are closest to the user and have sufficient computing power, effectively reducing overall processing latency.

3.3 Intelligent Resource Allocation Technology

Artificial intelligence-based resource allocation

algorithms can automatically adjust resource allocation strategies based on network status and user requirements, thereby achieving efficient resource utilization. Deep reinforcement learning algorithms, by defining states, actions, and reward functions, enable network models to select optimal actions according to the current state in order to maximize rewards. In the 6G integrated communication, sensing, and computing network, the state may include network load conditions, user location information, and service types; actions may include spectrum allocation and computing power allocation; and the reward function can be defined based on network performance metrics such as throughput and latency.

In the 6G integrated network, resource allocation must consider multiple objectives, such as communication quality, sensing accuracy, and computational efficiency. Multi-objective optimization resource allocation models can comprehensively consider these objectives to achieve optimal resource distribution. Multi-objective optimization problems are typically solved using methods such as the weighted sum method or the constraint method [6]. The weighted sum method combines multiple objective functions by summing them with specific weights, transforming the multi-objective optimization problem into a single-objective one for solution. The constraint method, on the other hand, treats some objectives as constraints, converting the multi-objective optimization problem into a constrained optimization problem for resolution.

Conclusion

In summary, the 6G integrated communication, sensing, and computing network, as a key developmental direction for future communications, features a layered architecture design that achieves deep integration of sensing, communication, computing, and applications. It offers advantages such as efficient interaction, powerful computing capabilities, flexible configuration, and broad applicability. Key technologies, including communication-sensing integration, computing power networks, and intelligent resource allocation, provide robust support for enhancing its performance and expanding its functionalities. As research progresses, the 6G integrated network is expected to demonstrate significant potential in fields such as intelligent transportation, healthcare, and industry. It will drive the digital transformation of society to new heights, ushering in a new era of intelligent connectivity for all things, and bringing unprecedented changes and opportunities to human life and the development of various industries.

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