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A Review of Research on Integrated Communication and Perception Technology

Jiale Yang

Shanghai ShangDe Experimental School, Shanghai, China
18721892480@163.com

Abstract. In recent years, with the continuous development of communication information technology, Integrated Sensing and Communication (ISAC) technology has gradually become an important research direction of future communication systems. The core idea is to realize the communication and perception functions through a set of hardware devices at the same time, which can improve the utilization efficiency of spectrum, hardware and other resources, and meet the diverse application scenarios of future mobile communication systems. This paper introduces the research background and significance of ISAC technology, and explains its importance and application potential in future communication networks. It also looks at the main technologies of ISAC, like designing combined signals, processing those signals, managing resources, and common uses of ISAC, such as smart transportation, smart healthcare, and the industrial Internet. The findings reveal that ISAC technology holds significant promise for enhancing future communication systems by optimizing resource utilization and enabling diverse applications, though addressing its inherent challenges will be crucial for its successful implementation and advancement.

Keywords: ISAC, Signal Processing, Integrated waveform design, Resource allocation

1. Introduction

As 5G networks are widely deployed and mature, expectations are heightened for the performance and functionality of future mobile communication systems. The next-generation 6G mobile communication technology will strive to achieve higher speed, lower latency, a larger number of connections, and support a wider range of application scenarios. In this context, the Integrated Communication and Perception (ISAC) technology emerged and has gradually become one of the hot directions in the research of 6G communication systems [1]. Traditionally, communication systems are mainly responsible for the transmission of information, while perception systems such as radar focus on target detection, positioning, tracking and other functions. Because the two are independent in terms of function, architecture, and signal processing, they lead to waste of spectrum resources, high hardware costs, and complex systems. ISAC technology breaks this traditional separation model and implements communication and sensing functions on the same hardware platform. This can not only improve spectrum utilization, but also reduce hardware costs, bring more powerful environmental perception and interaction capabilities to future communication

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systems, and meet the needs of emerging application scenarios such as intelligent transportation, intelligent healthcare and industrial Internet for communication and sensing integration.

This paper introduces the key technologies, application scenarios, and future development directions of Integrated Sensing and Communication, contributing to seamless integration of communication and sensing capabilities to meet the diverse needs of emerging applications.

2. Key technologies of ISAC

2.1. Integrated waveform design

Integrated waveform design, as one of the key technologies of ISAC, necessitates the development of a waveform that can meet the requirements of data transmission and achieve high-precision perception functions. Common integrated waveform design methods include orthogonal frequency division multiplexing (OFDM)-based waveform design, linear frequency modulation (Chirp) waveform design, and chaotic sequence-based waveform design etc [2]. In practical applications, it is necessary to select an appropriate integrated waveform design method according to different application scenarios and performance requirements, and optimize the waveform parameters to achieve a balance and improvement of communication and sensing performance.

The integrated waveform based on OFDM uses the orthogonality of the OFDM subcarrier to modulate the communication data to different subcarriers for transmission, and at the same time realizes the sensing function by modulating the amplitude, phase and other parameters of the subcarrier. This waveform is appropriate for complicated wireless communication scenarios and offers the benefits of high spectrum utilization and good resistance to multipath fading. OFDM technology has been widely employed in 5G communication networks and is compatible and feasible to adapt to ISAC systems [3-4].

The Chirp waveform is a waveform with a linear change in frequency over time and is widely used in radar perception systems. In the ISAC system, the Chirp waveform can be used to accurately measure the distance, velocity and other information of the target by adjusting parameters such as frequency change rate and pulse width, and can also be used for the modulation of communication data [5]. Its key advantages lie in its excellent range and velocity resolution, which enhance long-range perception and facilitate accurate detection of high-speed targets.

The integrated waveform based on chaotic sequence takes advantage of the randomness and broadband characteristics of chaotic signals to design a waveform with low interception probability and good autocorrelation characteristics [6]. This waveform enables high-precision perception while ensuring communication security, making it particularly well-suited for military and specialized applications that demand stringent security measures.

2.2. Signal processing techniques

Signal processing technology is essential for efficient communication and accurate sensing. In an ISAC system, receive signal processing must handle both communication signals and perception echo signals to extract useful information. For communication signal processing, it mainly includes demodulation, decoding, and channel estimation to recover the original data from the sender. For perception echo signal processing, it involves algorithms such as target detection, positioning, and tracking. The target detection algorithm determines whether there is a target and the approximate location of the target through the analysis of the received signal. The commonly used object detection algorithms include the Constant False Alarm Rate (CFAR) detection algorithm, which can maintain a constant false alarm probability in different noise environments and improve the accuracy of target detection [7]. The positioning algorithm accurately calculates the position coordinates of the target according to the time delay, angle and other information of the perception signal. For example, based on Time of Arrival (TOA), Time Difference of Arrival (TDOA), Angle of Arrival (AOA). Through the measurement of the signal by multiple receiving nodes, the principle of triangulation is used to achieve target positioning [8]. The tracking algorithm monitors the target's movement trajectory in real time, utilizing commonly employed methods such as the Kalman filter and particle filter. These algorithms predict the target's future state based on its historical data and current measurements, enabling stable and accurate tracking.

In addition, in order to improve the efficiency and accuracy of signal processing, it is also necessary to combine advanced digital signal processing technologies, such as adaptive filtering, multiple-input, multiple-output (MIMO), etc. The adaptive filtering technology can adjust the parameters of the filter in real time according to the statistical characteristics of the signal and noise, so as to achieve the best filtering effect, suppress noise interference, and improve signal quality. MIMO technology uses multiple antennas to transmit and receive signals, which can increase the channel capacity of the system, improve the performance of communication and perception, and has significant advantages in complex multipath propagation environments [9-10].

2.3. Resource allocation techniques

Reasonable resource allocation is the key to achieving efficient coordination between communication and sensing functions. In the ISAC system, resource allocation mainly includes the allocation of spectrum, power, and time resources.

When allocating spectrum, it is necessary to consider the different requirements of spectrum for communication and sensing, as well as the efficiency of spectrum reuse. It is necessary to avoid mutual interference between communication and perception signals on the spectrum, and also make full use of limited spectrum resources to improve the overall performance of the system. For example, a dynamic spectrum allocation strategy can be used to flexibly adjust the use of spectrum according to the real-time needs of communication and sensing services. When the communication traffic is large, it is essential to allocate more spectrum resources for communication. Conversely, if the sensing task is urgent or requires substantial bandwidth, the allocation for communication should be reduced to prioritize sensing needs [11].

When allocating power, it is necessary to consider that too high power will increase interference between nodes and waste energy, while too low power will affect the reliability of communication and the accuracy of sensing. Therefore, it is necessary to allocate the transmit power reasonably according to the channel status, service requirements, and other factors. The power control algorithm can be used to dynamically adjust the transmit power according to the signal strength feedback at the receiver to ensure the quality of the communication link and the effective coverage of the perception signal [12]. For example, when the quality of the communication link is good, the transmission power should be appropriately reduced to reduce the interference to other nodes; When conducting long-range perception or detecting weak targets, increase the transmitting power and improve the sensitivity of perception.

Time resource allocation is mainly to coordinate the time occupation of communication and perception [13]. Because communication and sensing tasks may have different temporal characteristics, for example, communication may take a long time to transmit a large amount of data, while sensing may require bursty detection at a specific moment. Therefore, it is necessary to design a reasonable time scheduling scheme to ensure that the communication and sensing tasks can be

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carried out in an orderly manner and do not conflict with each other. Time can be divided into different time slots, which are used for communication and perception operations. In each time slot, according to the priority and urgency of the task, specific time resources are further allocated to different communication or sensing services. Through reasonable time and resource allocation, the operation efficiency of the system can be improved, and the requirements of communication and perception real-time in different application scenarios can be met.

3. Cases of ISAC usage

3.1. Intelligent transportation

In intelligent transportation, ISAC has a wide range of application prospects. For autonomous driving, the vehicle equipped with ISAC system can sense the location, speed, and direction of movement of surrounding vehicles, pedestrians, road facilities, while simultaneously ensuring high-speed and reliable communication with other vehicles and transportation systems. For the intelligent traffic management system, the base station or sensor node on the roadside can monitor traffic through ISAC technology, perceive the distribution of vehicles on the road, driving speed and other information, and send this information to the traffic management center through the communication link. Based on these real-time data, the traffic management center optimizes the timing scheme of traffic lights, realizes reasonable traffic flow and alleviates traffic congestion. Zhang proposes an intelligent vehicle networking system framework based on integrated sensing and communication design, which is of great significance for improving the service level of the command and traffic system [14].

3.2. Intelligent medical field

In smart healthcare, ISAC can provide strong support for applications like telemedicine and medical monitoring [15]. In the telemedicine cases, doctors can engage in high-definition video communication with patients through the ISAC system while simultaneously utilizing its perception capabilities to obtain real-time physiological parameters, such as heart rate, blood pressure, and body temperature. Doctors use this data to make remote diagnoses and develop treatment plans. In terms of medical monitoring, the ISAC system within the hospital can monitor the patients real-timely, sensing the patient's activity status, sleep status, etc. Once a patient is found to be abnormal, the system can send an alert to the medical staff through the communication function in time, so that the medical staff can take timely measures. ISAC technology can also be used for communication and collaboration between medical devices, such as information exchange and collaboration between surgical robots and other medical devices, to improve the accuracy and safety of surgery.

3.3. Industrial internet

In the field of industrial Internet, ISAC technology helps to realize the intelligence and automation of industrial production [16]. In a smart factory, the ISAC system can send these data to the industrial control system by sensing the vibration, temperature, current and other parameters of the equipment, combined with the communication function, to achieve real-time monitoring of the operating status of the equipment. Once a potential failure of the equipment is found, the system can issue an early warning in time and communicate the maintenance instructions to the maintenance personnel through the communication network to arrange the maintenance plan. In industrial logistics, ISAC can be used to track and locate goods, and by installing labels with ISAC functions

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on the packaging of goods , the logistics system can perceive the location and transportation status of goods in real time, and realize the visual management of the logistics process. At the same time, the ISAC system can also communicate with the automated logistics equipment in the factory, coordinate the handling and storage of goods, and improve the intelligence level of industrial logistics.

4. Challenges and prospects

ISAC technology still faces a lot of challenges and problems which are waiting for further study.

4.1. In terms of system design and integration

Achieving the deep integration of communication and sensing functions—ensuring communication quality without compromising sensing performance, or enhancing sensing accuracy without impacting communication efficiency—remains a critical challenge that requires further research [1]. ISAC will be deeply integrated with artificial intelligence (AI) technology to further improve the performance and intelligence of the system. AI technology can further optimize processes such as resource allocation, signal processing, and decision-making for ISAC systems. Machine learning algorithms are used to analyze a large amount of communication and perception data to predict the communication traffic volume and perception task requirements, so as to achieve more intelligent dynamic resource allocation and improve resource utilization. In terms of signal processing, deep learning algorithms can be used for object detection and recognition, and through the learning of a large number of sample data, the accuracy of object detection and recognition can be improved, especially in complex environments, which can effectively improve the perception performance of ISAC systems. AI-based decision-making algorithms can make more rational decisions based on real-time information from communication and perception.

4.2. In terms of hardware implementation

There are still certain technical difficulties in developing low-cost, low-power, and high-performance ISAC hardware devices, and breakthroughs need to be made in chip design and antenna technology. With the increasing requirements for communication and sensing performance, frequency resources are becoming more and more strained, and ISAC systems will evolve to higher frequency bands, such as terahertz (THz) bands. The terahertz frequency band can provide ultra-high-speed data transmission to meet the needs of future high-definition video transmission, virtual reality (VR), augmented reality (AR) and other high-traffic services. Terahertz signals can accurately detect and image small targets, and are suitable for biomedical detection, safety inspection, and other fields. However, the terahertz frequency band also faces problems such as large signal propagation loss and high hardware implementation, and it is necessary to further study new antenna technology, modem and demodulation technology and hardware design methods to overcome these challenges and promote the application and development of ISAC systems in the terahertz frequency band.

4.3. In terms of pratical applications and compatibility

The compatibility of the ISAC system with existing communication and perception systems also needs to be properly addressed to achieve a smooth transition and work together. ISAC system will not only be limited to the integration of communication and perception functions, but also deeply

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integrate and collaborate with other fields such as computing and storage to form an integrated information processing system. Through the coordinated work of communication, sensing, computing, and storage, more efficient data processing and information utilization can be realized. For example, in a smart city, the ISAC system senses various information in the city, such as traffic flow, environmental parameters, etc., and transmits this data to edge computing nodes or cloud computing centers for real-time processing and analysis through the communication network, while using storage resources to exchange historical data.

5. Conclusion

As a key technology direction of 6G and future wireless networks, the integration of communication and perception is promoting the transformation of information systems from "connection empowerment" to "perception intelligence" through the in-depth collaboration of resources and functions. In this paper, it reviewed the key technologies of ISAC (such as waveform design, resource allocation, and signal processing) and typical application scenarios. It also reveals its significant advantages in improving spectrum efficiency, reducing hardware overhead, and enhancing environmental awareness. At present, there are still challenges such as the trade-off between perception accuracy and communication rate, dynamic scene adaptation, and the lack of standardized frameworks. With the deepening of research and the iteration of technology, the integrated synaesthesia system will evolve in the direction of efficiency, intelligence, and integration in the future, realize the deep collaboration of communication, perception and computing, provide users with a richer and high-quality service experience, and help build a future network ecology of Internet of Everything and intelligent perception.

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