A Comprehensive Survey of ISAC Technology: Fundamental Principles, Research Progress, and Future Trends

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Abstract. Traditional wireless communication and sensing systems have long been separated, lacking synergy in spectrum, hardware, and signal processing, which leads to low resource utilization and high costs. With the evolution from 5G-A to 6G, the demand for "communication-sensing-decision" integration has surged in scenarios such as intelligent transportation, and traditional architectures can hardly meet this demand. The integrated sensing and communication (ISAC) technology, which realizes functional integration by sharing spectrum, hardware, and algorithms, has become a core direction in breaking through the bottleneck. Its research popularity has risen rapidly in the past five years, but the achievements in the field are scattered and lack systematic sorting. This paper aims to construct a panoramic review of ISAC, expound its technical principles, sort out research progress and breakthroughs, summarize development trends, and consider current challenges and prospects. This effort will integrate scattered research results, establish a systematic ISAC technical knowledge system, provide references for practical implementation, and point out future directions for researchers.

Keywords: Integrated Sensing and Communication (ISAC), sharing spectrum, hardware and algorithms.

1. Instruction

As 5G-Advanced (5G-A) technologies rapidly evolve toward the sixth-generation (6G) wireless communication systems, emerging application scenarios such as intelligent transportation, smart cities, industrial IoT, autonomous driving, and remote healthcare are placing increasingly stringent demands on the integration of communication, perception, and decision-making capabilities. These scenarios require high-speed, low-latency, and reliable communication services and require real-time environmental sensing and intelligent decision-making in a tightly coupled manner to enable more efficient, safe, and intelligent operations. However, traditional wireless communication and sensing systems have long been designed and operated independently, resulting in low resource utilization, increased system complexity, and poor synergy, which hinder their ability to meet these multifaceted and dynamic application requirements.

Integrated Sensing and Communication (ISAC) technology has emerged as a promising solution to address these challenges. By sharing spectrum resources, hardware platforms, and signal processing algorithms, ISAC deeply integrates communication and sensing functionalities, thereby improving spectral efficiency, reducing system cost and power consumption, and enabling multi-functional collaborative optimization. This paradigm shift accelerates the evolution of wireless systems and provides a solid technological foundation for future intelligent applications. Over the past five years, there has been a surge of research interest and progress in ISAC, spanning fundamental theory, key enabling technologies, system architectures, and practical deployments. Nevertheless, the current body of work remains fragmented and lacks a comprehensive and systematic review, which limits academia and industry from fully understanding and leveraging ISAC's potential.

In response to this gap, this paper aims to establish a panoramic review framework for ISAC technology by systematically elucidating its fundamental principles, summarizing the latest research advances, identifying technical bottlenecks, and exploring future development trends. Through this comprehensive survey, we intend to provide clear guidance and a cohesive knowledge base for researchers and practitioners, thereby accelerating the transition of ISAC from theoretical exploration to large-scale practical application. Ultimately, this will contribute to the leap-forward advancement and intelligent transformation of next-generation wireless communication systems.

2. Basic Principles

2.1 Definition and Core Connotation of ISAC

Integrated Sensing and Communication (ISAC) is a core technology for the evolution from 5G-A to 6G networks. Its principle is to achieve deep integration of sensing and communication by sharing the same spectrum, hardware resources, and signal processing modules, thereby improving resource utilization and enabling functional collaboration between sensing and communication [1]. Essentially, the significance of ISAC technology lies in simultaneously providing high-quality environmental sensing capabilities and communication capabilities in the same system through advanced technologies such as Multiple-Input Multiple-Output (MIMO), millimeter waves, and terahertz (THz) [2].

The main goals of ISAC are to achieve two types of gains: one is integration gain, which reduces redundancy and improves energy efficiency and spectrum efficiency by sharing spectrum, hardware, and computing resources [3,4]; the other is synergy gain, which enhances the performance of both sensing and communication through mutual assistance, ultimately improving the overall system performance [4].

2.2 Mutual Assistance between Sensing and Communication

Specifically, sensing technology can conduct three-dimensional analysis by detecting the surrounding environment and obstacles, enabling the information transmission network to dynamically adapt to channel conditions, achieve optimal resource allocation, and enhance anti-interference capabilities, thereby realizing sensing-assisted communication. Similarly, signals of different frequency bands can provide differentiated capability improvements for sensing technology, and several types of channel resources can be used in mutual assistance and cross-application, thus achieving communication-assisted sensing [5].

2.3 Scenario-based Classification of ISAC

ISAC can be classified according to various indicators for different scenarios. For example, in the field of intelligent vehicles, ISAC can be divided into functional-level ISAC (fISAC) and signal-level ISAC (sISAC): the former integrates radio frequency (RF) and non-RF sensors (such as vehicle-mounted radars and cameras), while the latter focuses on the unified design of radio frequency signals [6]. These principles form the basis for applying ISAC in intelligent transportation, unmanned aerial vehicle communication, and smart homes.

3. Research Progress

In recent years, Integrated Sensing and Communication (ISAC) technology has witnessed significant breakthroughs across theoretical foundations and practical applications. On the theoretical front, advancements have been made in understanding the fundamental principles that govern the joint design of sensing and communication systems, including novel waveform designs, resource allocation strategies, and algorithmic frameworks. Simultaneously, in terms of application, ISAC has been successfully demonstrated in various emerging fields such as intelligent transportation, smart cities, autonomous driving, and industrial automation, showcasing its potential to enhance system efficiency, reduce costs, and enable new functionalities. These rapid developments have deepened the academic understanding of ISAC and accelerated its translation into real-world deployments, marking a critical step toward the future of integrated wireless networks.

3.1 Waveform and Signal Design Schemes

Regarding theory, ISAC has two central waveform and signal design schemes: non-overlapping resource allocation and fully unified waveform. The former separates sensing and communication signals through orthogonal means [4,7]; the latter is divided into three different types with respective focuses — Sensing-Centered Design (SCD), Communication-Centered Design (CCD), or Joint Design (JD), which aim to design waveforms that can satisfy both functions simultaneously [1,7].

3.2 Research on Transmit Beamforming

In the research on transmit beamforming, a downlink ISAC system framework has been constructed to realize the coordination between multi-user communication and target sensing. Two receivers are distinguished based on the ability to handle radar signal interference: Type-I receivers cannot eliminate radar interference, while Type-II receivers can achieve interference cancellation.

A new "maximization of minimum weighted pattern gain" criterion is proposed for design criteria, focusing on improving the worst-case sensing performance at angles of interest. Regarding optimization methods and performance analysis, semi-definite relaxation (SDR) technology is used to solve the non-convex optimization problems formed by different design criteria and receiver types, and the global optimal solution is obtained. Numerical results further verify that the sensing performance of Type-II receivers is better than that of Type-I receivers and traditional designs; the new criterion has better sensing performance at angles of interest, and its computational complexity is lower than that of conventional pattern matching designs [8].

3.3 Performance Metrics and Limits

The performance metrics of ISAC technology are also being increasingly clarified. In Gaussian channels, the performance metrics for waveform design focus on two key "corner points" in the region, which correspond to extreme optimization objectives respectively: the maximum communication rate under the constraint of minimum sensing CRB (with priority given to ensuring sensing accuracy), and the minimum sensing CRB under the constraint of maximum communication rate (with priority given to ensuring communication performance), each having its advantages and disadvantages [9]. In addition, basic theoretical research has also revealed the performance limits of ISAC [10], providing clear theoretical guidance for subsequent studies.

3.4 In-depth Coordination between Communication and Sensing

Sensing-aided communication optimization has achieved advantages in in-depth coordination between communication and sensing: first, accelerated beam training. Using radar to predict user directions in advance reduces the beam scanning overhead for initial millimeter-wave access. For example, radar-aided schemes can reduce training time by 77%; second, blockage management. Cameras are used to predict the movement of obstacles, beams, or frequency bands, and they are switched in advance to avoid communication interruptions, with a prediction accuracy of over 90%.

Regarding communication-aided sensing, millimeter and sub-terahertz waves, relying on high resolution, have achieved centimeter-level positioning. Through the coordination of radar and signal base stations, bistatic SLAM (Simultaneous Localization and Mapping) breaks through the limitation that positioning depends on Line-of-Sight (LoS) via multi-base station collaboration; monostatic SLAM constructs local environmental maps using the reflection of its own transmitted signals, which is suitable for scenarios such as indoor navigation. The terahertz frequency band has achieved 12cm-level trajectory reconstruction [5].

3.5 Application Scenarios and Industrialization Progress

In addition, ISAC has made varying progress and breakthroughs in different application scenarios and fields. A fiber-optic ISAC based on optical fiber communication uses LFM (Linear Frequency Modulated) light as the optical carrier for communication. This can effectively suppress the SBS

(Stimulated Brillouin Scattering) effect while enhancing SPM (Self-Phase Modulation), thereby effectively improving various indicators of traditional optical fiber communication, achieving larger bandwidth, higher power, and code rate, and realizing distributed vibration sensing in 24.5km optical fibers [11].

In the field of unmanned aerial vehicles (UAVs), single-UAV ISAC can improve coverage flexibility and performance through the design of different frame protocols (Co-ISAC, TDM-ISAC, Hybrid-ISAC) and the joint optimization of trajectory planning and resource allocation; multi-UAV systems expand coverage and improve accuracy through interference coordination and collaborative sensing [2].

Certainly, ISAC has gradually moved towards practical applications to a certain extent. For example, in vehicle communication networks, ISAC has realized sensing-aided beam tracking [6]; in UAV networks, it has achieved communication-aided sensing [2]; in smart homes, it has realized human activity recognition through WiFi signals [3,12].

Moreover, ISAC continues to advance in standardization and industrialization. 3GPP has evolved from 5G positioning to 6G sensing; ETSI has established an ISAC Industry Specification Group, specifying 32 core application scenarios including smart homes, transportation, and industry; at the industrial chain level, enterprises such as Huawei and Ericsson have carried out ISAC prototype verification, and integrated millimeter-wave radar and communication chips have entered the testing stage [5].

4. Future Trends

The future development of ISAC technology will primarily focus on three main directions. The first direction involves interdisciplinary integration, emphasizing the collaboration and fusion of knowledge from various fields such as wireless communications, signal processing, artificial intelligence, and sensing technologies. The second direction centers on personalized scenario adaptation, aiming to customize ISAC solutions to meet the unique requirements and characteristics of different application scenarios, enhancing flexibility and efficiency. The third direction highlights the need for further basic theoretical research to deepen understanding of fundamental principles and overcome existing technical challenges, laying a stronger foundation for practical advancements and innovations in ISAC systems.

4.1 Integration with Emerging Technologies

First, integration with emerging technologies is a significant trend: ISAC can be combined with edge intelligence, using Federated Learning (FL) to realize privacy protection of distributed sensing data and model training; further collaboration with Reconfigurable Intelligent Surfaces (RIS) can regulate channels through reflection, expand sensing coverage, and enhance communication reliability [12]; it can be integrated with unmanned aerial vehicles (UAVs), utilizing the mobility of UAVs to achieve dynamic sensing and communication coverage optimization, but issues such as interference management and trajectory coordination remain to be solved [2,4]. Combining with AI, deep learning processes unstructured sensing data (such as radar echoes, images) and communication channels, realizing joint waveform optimization, interference suppression, and environmental modeling. For example, Transformer networks have been applied to millimeter-wave positioning, achieving 20cm-level tracking accuracy [5].

4.2 Demand for Personalized Scenario Optimization

Meanwhile, the demand for personalized scenario optimization of ISAC technology is prominent: in vehicle communication networks, it is necessary to integrate multi-modal sensors further and improve the robustness of environmental perception through a "synesthesia" mechanism [6]; in 6G scenarios, ISAC technology faces issues such as high path loss in the terahertz frequency band and broadband sensing requirements, thus requiring the development of new waveforms and signal processing algorithms [4,7].

With the addition of specific technologies, for example, in optical fiber networks, their application scenarios can be significantly expanded. Fiber-optic ISAC can utilize distributed sensing capabilities to realize infrastructure monitoring such as safety monitoring of urban underground pipelines (gas, water supply), structural health assessment of bridges and tunnels, and detecting submarine earthquakes and ocean dynamics. Compared with traditional ISAC solutions that require redesigning and deploying a complete set of schemes, it only needs to embed sensing functions into existing optical fiber communication networks (such as metropolitan area networks, passive optical networks) without additional deployment of sensing optical fibers, thus realizing the functions of communication networks, reducing costs, and improving efficiency. Moreover, fiber-optic ISAC has vibrant and flexible expansion schemes regarding distance, frequency band, and architecture [11].

4.3 Challenges and Limitations

However, there are still many challenges to be addressed at both the theoretical and engineering levels, including the quantitative description of the performance limits of sensing and communication, low-complexity joint optimization algorithms, security mechanisms [2,10,12], the expansion of system models along with the proposal of new performance indicators and collaborative strategies [8], and the advancement of standardization [7]. Signals in different frequency bands have advantages and disadvantages, so it is necessary to adapt to varying scenarios through intelligent frequency band selection and solve the problems of cross-band synchronization and hardware compatibility. New scenarios require new channel models, which should break through the traditional far-field assumption to support the coexistence of centimeter-level positioning and Tbps-level communication [5]. These directions will promote the development of ISAC from the laboratory to large-scale applications, making it a core technology in the new generation of the information field.

5. Discussion

As one of the key enabling technologies for 6G, Integrated Sensing and Communication (ISAC) achieves deep fusion of communication and sensing by sharing spectrum, hardware, and signal processing resources, thereby significantly improving spectrum efficiency, reducing energy consumption and hardware redundancy, and enhancing overall system synergy. In recent years, substantial progress has been made in unified waveform design, transmit beamforming optimization, performance metric modeling, and theoretical limit analysis, as well as in application scenarios such as vehicular networks, UAV communications, optical fiber systems, and smart homes. Some achievements have advanced to prototype validation, standardization, and industrialization stages. However, significant challenges remain in bridging the gap from theoretical research to large-scale engineering deployment. These include dynamically balancing communication and sensing performance in varying scenarios, designing low-complexity joint optimization algorithms capable of real-time operation, achieving cross-band and cross-platform hardware compatibility, developing efficient interference management and resource scheduling mechanisms, and ensuring the security and privacy of sensitive sensing data. In high-frequency applications such as millimeter-wave and terahertz bands, severe path loss and the complexity of broadband signal processing impose additional demands on system architecture and algorithm design.

In contrast, emerging issues such as near-field propagation, non-line-of-sight positioning, and large-scale MIMO array control require further investigation. Future development trends will involve deep integration with emerging technologies such as artificial intelligence, reconfigurable intelligent surfaces (RIS), and unmanned aerial vehicles (UAVs) to realize more intelligent, flexible, and scenario-adaptive ISAC systems. Personalized solution design will be essential for diverse applications, such as multimodal sensing fusion for vehicular networks and distributed structural health monitoring in optical fiber systems. Furthermore, accelerating standardization, hardware integration, and industrial ecosystem collaboration will be crucial to driving ISAC from laboratory research to large-scale deployment, ultimately supporting "communication–sensing–decision" integrated services in diverse 6G-era scenarios such as intelligent transportation, smart cities, and the industrial Internet.

6. Conclusion

This review has examined the current research landscape on cooperative cell-free massive MIMO systems without cellular boundaries, highlighting key developments in system architecture, channel estimation, user association, and interference management. The collective findings indicate that cell-free architectures hold great promise for addressing the limitations of traditional cellular systems by providing uniformly high spectral and energy efficiency across the coverage area. By leveraging distributed antennas and centralized coordination, these systems can mitigate inter-cell interference and enhance user fairness, especially in scenarios with high user density or uneven traffic distribution.

Nevertheless, several open challenges remain. The practical implementation of large-scale cell-free networks requires scalable fronthaul solutions, low-complexity signal processing algorithms, and efficient resource allocation strategies that adapt to dynamic network conditions. Moreover, hardware impairments, synchronization issues, and the integration of cell-free MIMO with emerging technologies such as mm Wave, THz communications, and intelligent reflecting surfaces warrant further investigation. There is also a pressing need to explore the interplay between physical layer design and higher-layer protocols to ensure seamless end-to-end performance.

Future research should bridge the gap between theoretical performance limits and real-world deployments by developing robust, cost-effective, and energy-efficient designs. Interdisciplinary approaches combining advanced optimization, machine learning, and network virtualization may offer promising pathways to unlock the full potential of cell-free massive MIMO systems. By overcoming these challenges, cell-free networks could become a cornerstone technology for 6G and beyond, enabling ubiquitous, high-quality wireless connectivity.

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