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A Review of Multi-Base Station Collaborative Target Sensing Based on Integrated Sensing and Communication

Kai Cui[1], Hui Chen[2], Jianwei Zhao[1], Mengyue Li[1], Binhua Wei[1]

[1]Rocket Force University of Engineering, Xi'an 710025, Shaanxi, China

[2]Academy of Aerospace Solid Propulsion Technology, Xi'an 710025, Shaanxi, China

Abstract: Integrated sensing and communication (ISAC) technology for multi-base station collaborative target sensing has become a research hotspot due to its advantages in scenarios like the low-altitude economy and intelligent transgportation. This paper reviews the key technologies and applications of multi-base station ISAC collaborative sensing. First, the research background and significance are presented. It is pointed out that the development of the low-altitude economy imposes requirements of high precision, wide coverage, and real-time performance on wireless sensing technologies. Next, the domestic and international research status is analyzed, covering the development of single-base station ISAC technology, the system architecture of multi-base station collaborative sensing, and representative technologies. The existing technical challenges are also pointed out. Then, the models and basic theories of multi-base station ISAC systems are elaborated, including system architecture, physical models of target perception, and performance evaluation indicator systems. On this basis, technologies such as signal-level collaboration, data-level fusion, and symbol-level fusion strategy are discussed in detail. Finally, typical application scenarios and system implementation are analyzed, such as UAV tracking in the low-altitude economy and vehicle-infrastructure collaboration in intelligent transportation. The current technical challenges and future research directions are also summarized.

Keywords: integrated sensing and communication; multi-base station collaborative sensing; parameter estimation; time-frequency synchronization; data fusion

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1. Introduction

As an emerging economic form, the low-altitude economy, relying on application scenarios such as UAV logistics and urban air mobility, is promoting the intelligent utilization of urban spatial resources and service model innovation[1]. However, requirements such as dense UAV operations and dynamic target monitoring impose strict demands for high precision, wide coverage, and real-time performance on wireless sensing technologies. Traditional single-base station sensing is limited by line-of-sight (LoS) propagation and signal attenuation, making it difficult to meet the multi-target collaborative monitoring needs in complex urban environments. ISAC technology achieves symbiotic multiplexing of communication and sensing functions through deep integration of hardware and resources, providing a solution for low-altitude economic scenarios that balances spectral efficiency and sensing accuracy[2,3]. The multi-base station collaborative sensing architecture, through signal fusion of distributed nodes, can break through the sensing range limitations of single base stations, demonstrating significant advantages in improving target positioning accuracy and enhancing robustness in non-line-of-sight (NLoS) scenarios[4-6]. Such technological breakthroughs provide key support for applications like intelligent traffic management and emergency monitoring, becoming one of the core development directions for 6G and future wireless systems.

Single-base station ISAC technology has evolved from early waveform design to the stage of joint resource optimization. However, constrained by physical aperture and signal power, its sensing range and resolution face obvious bottlenecks in complex scenarios[7,8]. Multi-base station collaborative sensing has gradually become the mainstream technical path to break through this bottleneck through spatial diversity and information fusion. In terms of system architecture, centralized fusion centers achieve high-precision joint processing through real-time data interaction but face bandwidth pressure on backhaul links; distributed architectures rely on edge computing capabilities to reduce communication overhead but suffer from cumulative synchronization errors[9,10]. Representative technologies include: a two-stage parameter estimation framework based on Maximum Likelihood (ML)[1], which improves positioning accuracy through far-field hypothesis initialization and near-field fine estimation; a multi-target tracking method based on Joint Probability Data Association (JPDA) and Extended Kalman Filter (EKF)[2], which effectively solves the trajectory association problem for distributed nodes; sensing enhancement technologies using Reconfigurable Intelligent Surfaces (RIS) to reconstruct NLoS channels[3]; and the coexisting waveform design for distributed MIMO radar and communication proposed in Reference[11], which achieves improved resource utilization. Nevertheless, existing studies still face technical challenges in aspects such as multi-base station time-frequency synchronization accuracy, heterogeneous node collaboration efficiency, and dynamic scene adaptability[5,12]. Reference [13] points out that phase ambiguity in NLoS scenarios leads to reduced accuracy of traditional synchronization algorithms, while the ISAC topology switching mechanism proposed in Reference [14] provides a new approach for dynamic scene adaptation.

This review focuses on the technological evolution and application practices in the field of multi-base station ISAC collaborative sensing. It starts from near-field/far-field propagation models, analyzes the theoretical foundations and performance boundaries of multi-base station collaborative sensing, and then integrates representative technical paths such as distributed beamforming, time-frequency synchronization, and super-resolution estimation around dimensions including signal processing, data fusion, and scene adaptation. By summarizing technical adaptation schemes in typical application scenarios, it expounds on the common challenges of current technologies in terms of synchronization accuracy and computational complexity.

2. System Models and Fundamental Theories

2.1. Multi-Base Station ISAC System Architecture

The multi-base station ISAC system typically employs a distributed multiple-input multiple-output (MIMO) array architecture. At the hardware level, hybrid digital-analog beamforming is commonly used to balance performance and cost overhead[1,5]. The system signal model is based on orthogonal frequency division multiplexing (OFDM) as a typical carrier, and the coexistence of communication and sensing functions is achieved through time-frequency resource allocation. The subcarrier spacing and symbol duration must satisfy the time-frequency orthogonality constraints [3,6]. The collaborative topology determines the system performance characteristics: The centralized architecture achieves global data fusion through a central processing unit, which is suitable for high-precision scenarios but is limited by the backhaul link bandwidth; The distributed architecture relies on edge computing capabilities to reduce communication overhead, but it faces the problem of cumulative synchronization errors; The hierarchical topology achieves a trade-off between local and global collaboration through regional cluster head nodes[12,15]. The mesh topology optimization algorithm proposed in [16] further improves the collaborative efficiency of distributed nodes, while the ultra-dense network architecture in [17] achieves a balance between sensing coverage and energy consumption by optimizing base station density.

2.2. Basic Theory of Target Sensing

The physical model of target sensing is defined by near-field and far-field propagation mechanisms: When the distance between the target and the base station is less than the Rayleigh distance ($D_{ff} = 2D^2 / \lambda$, where D is the array aperture and λ is the wavelength), the electromagnetic wave exhibits spherical wave characteristics, and the array response needs to consider both angle and distance parameters; Under far-field conditions, it can be simplified to a plane wave model, and angle estimation becomes the core task[1,12]. Multipath effects and NLoS propagation significantly affect sensing accuracy. Reflection components in urban environments may introduce false targets, and the absence of direct paths in NLoS scenarios can significantly increase positioning errors[3,15]. Synchronization error is a key challenge for multi-base station collaboration. Phase inconsistency caused by clock offset accumulates with distance, and its time-frequency domain impact can be modeled and analyzed through channel reciprocity[5,11]. Reference [13] further reveals the propagation law of synchronization error under multipath channels, and the phase calibration method based on reciprocity proposed in [14] provides theoretical support for NLoS scenarios.

2.3. Performance Evaluation Index System

Localization accuracy is usually quantified by the Cramér-Rao lower bound (CRLB) and the root mean square error (RMSE). The former characterizes the theoretical limit of unbiased estimation, while the latter evaluates the actual algorithm performance through statistical simulation[2,4]. Detection probability and false alarm probability measure target identification capability, while computational complexity and communication overhead are key constraints for system engineering implementation. The computational complexity of centralized processing increases cubically with the number of base stations, while distributed algorithms reduce overhead through local processing[5,18]. Multi-target resolution capability needs to meet the spatial resolution criterion, and anti-interference performance is assessed through indicators such as the SINR. These parameters together form the theoretical performance boundary of the multi-base station ISAC system[19,20]. The joint communication-sensing performance trade-off model proposed in [21] provides a quantitative framework for index optimization, while the energy-efficient perception index system in [22] expands the traditional evaluation dimension.

3. Multi-Station Collaborative Target Sensing Technology

3.1. Signal-Level Collaborative Sensing Method

Signal-level collaborative sensing takes physical-layer signal processing as the core, achieving sensing performance improvement through distributed waveform design and joint parameter estimation of multiple base stations. The distributed beamforming technology realizes energy focusing by optimizing array weights, and its theoretical foundation includes a two-stage estimation framework based on Maximum Likelihood (ML). In the first stage, initial target parameters are obtained under the far-field assumption. If the target is detected to be in the near field, the framework switches to a spherical wave model for fine estimation, which reduces array response mismatch errors in near-field scenarios through model adaptation[1]. The codebook design for near-field beam focusing must meet the constant-gain coverage requirement, realizing uniform energy radiation by optimizing the amplitude-phase distribution in the target area. Mathematically, this can be reduced to a constrained least-squares problem, often solved by methods such as semidefinite relaxation[1,5]. The super-resolution synchronization algorithm proposed in Reference [23] achieves nanosecond-level offset estimation in low signal-to-noise ratio scenarios, while the joint time-frequency synchronization and target localization framework in Reference [24] further improves collaboration efficiency.

3.2. Data-Level Fusion Sensing Strategy

Data-level fusion enhances sensing robustness through cross-base station information integration, with its technical system covering state-space modeling and multi-source information association. The Joint Probabilistic Data Association (JPDA) and Extended Kalman Filter (EKF) form a classic framework for multi-target tracking. JPDA solves the data association ambiguity by constructing a measurement-target association probability matrix, while EKF uses the state-space model to realize recursive estimation of target trajectories. Their combination effectively reduces the probability of trajectory fragmentation in dense target scenarios[2,18]. The matrix pencil (MP)-based super-resolution estimation models signals as superpositions of exponential signals, achieving parameter extraction through constructing Hankel matrices and eigenvalue decomposition. This method exhibits higher resolution than FFT-class methods in low signal-to-noise ratio scenarios[5].

3.3. Symbol-Level Fusion Strategy

The symbol-level fusion strategy achieves high-precision positioning by leveraging the phase characteristics of communication signals, with its theoretical basis lying in that the range-Doppler information carried by OFDM symbols can be extracted through phase decoupling. Specifically, symbol-level processing avoids information loss in parameter estimation by preserving carrier phase information, improving positioning accuracy by 10%-30% compared to decision-level fusion (which only uses classification results)[6]. The performance boundary of data-level fusion is defined by information entropy theory: when the mutual information of data between base stations exceeds a threshold, the fusion gain grows logarithmically with the number of nodes, a characteristic that provides a theoretical basis for node scale design in distributed fusion architectures[2,6].

4. Typical Application Scenarios and System Implementation

4.1. Low-Altitude Economy and UAV Tracking

The low-altitude economy scenario imposes high-precision requirements on real-time positioning and trajectory monitoring of UAVs. A multi-base station ISAC system achieves wide-area coverage and dynamic target tracking through distributed collaborative sensing. The system architecture typically adopts a hierarchical deployment model: the edge layer consists of a sensing network formed by multiple base stations, while the central layer realizes global trajectory association through a fusion center. Its theoretical foundation lies in the state-space model based on Kalman filtering and geometric positioning principles[4,15]. Dynamic topology management technology predicts and switches the combination of primary and auxiliary base stations according to UAV movement trajectories, optimizing sensing performance by maximizing the Geometric Dilution of Precision (GDOP). Mathematically, this essence represents an optimal configuration problem for time-varying observation matrices[4]. The time-division multiplexing mechanism of communication and sensing resources employs dynamic frame structure design, maintaining sensing update rates while ensuring communication link throughput. This is theoretically supported by a resource utility maximization model based on the Lagrange multiplier method[1,15]. The UAV-assisted ISAC network deployment scheme proposed in Reference [21] expands the sensing coverage of traditional ground base stations through dynamic UAV base station movement to fill blind spots, while the multi-UAV collaborative tracking algorithm in Reference [24] enhances target resolution capability in dense scenarios.

4.2. Intelligent Transportation and Vehicle-Road Collaboration

Multi-base station ISAC technology in intelligent transportation systems aims to achieve vehicle positioning, trajectory prediction, and traffic situation awareness, with its system architecture following a three-layer collaborative framework of vehicle-road-cloud. Roadside base stations simultaneously carry communication data and sensing signals through MIMO-OFDM waveforms, realizing centimeter-level estimation of vehicle positions using symbol-level phase information. The technical core is joint range-Doppler estimation based on OFDM time-frequency domain characteristics[6,18]. The vehicle-road collaboration protocol adopts a hybrid data fusion strategy: edge-layer base stations perform local parameter estimation to reduce backhaul bandwidth requirements, while the central layer achieves multi-vehicle trajectory association through distributed Kalman filtering. This architecture can control positioning delay within 50 ms in high-dynamic scenarios[2,6]. Anti-multipath interference technology distinguishes direct and reflected path signals through environment map-assisted multipath identification algorithms, theoretically founded on signal feature classification models based on clustering analysis[3,15]. The vehicle-road collaborative sensing protocol based on 5G-V2X proposed in Reference [22] realizes joint processing of communication and radar signals, while the multi-base station collaborative speed measurement algorithm in Reference [16] improves vehicle speed estimation accuracy in highway scenarios.

5. Technical Challenges and Development Trends

5.1. Key Technical Challenges

Multi-base station ISAC collaborative sensing faces multiple technical bottlenecks in both theoretical and engineering implementations. In terms of synchronization accuracy, clock offsets and carrier frequency offsets between distributed nodes introduce phase inconsistency, whose time-frequency domain effects accumulate with distance. When the clock deviation between base stations reaches 1 *ns*, the positioning error of a target at 200 *m* can exceed 1 *m*[5,11]. Although existing air-interface synchronization technologies can achieve nanosecond-level offset estimation through channel reciprocity, the phase ambiguity problem caused by multipath signals in NLoS scenarios remains unsolved, essentially an underdetermined problem of time-frequency domain observation equations[5]. Computational complexity and communication overhead constitute dual constraints for system implementation: the calculation amount of centralized fusion grows cubically with the number of base stations, while the consistency protocol of distributed algorithms introduces additional communication overhead. This “accuracy-efficiency” trade-off is particularly prominent in large-scale networks[2,6].

In NLoS and multi-target interference scenarios, the uncertainty of signal propagation models significantly reduces sensing robustness. Multipath reflections in urban environments lead to false target misjudgments, while the absence of direct paths in NLoS scenarios increases positioning errors by over 50%[3,15]. Existing RIS (Reconfigurable Intelligent Surface)-assisted methods can reconstruct line-of-sight links, but optimizing the phase control matrix is essentially a high-dimensional non-convex problem, with the computational complexity of its optimal solution increasing exponentially with the array scale[3]. Multi-target interference manifests as parameter estimation ambiguity caused by signal subspace overlap. Traditional super-resolution algorithms struggle to effectively resolve targets when the spacing is less than half a wavelength, with their theoretical limits jointly determined by array aperture and signal bandwidth[1,18].

5.2. Future Research Directions

Future technological evolution will focus on improving sensing performance and scene adaptation. The deep integration of artificial intelligence and signal processing is a core development direction. An end-to-end sensing framework based on deep neural networks can automatically learn the spatio-temporal features of multi-base station signals, achieving adaptive resource allocation and parameter estimation in dynamic scenarios. Its theoretical foundation lies in the application of representation learning and reinforcement learning in unstructured signal processing[1,5]. Heterogeneous network collaborative sensing architectures construct multi-layered sensing networks by fusing cellular base stations, UAV nodes, and intelligent surfaces. The key lies in cross-standard node spatio-temporal registration and data fusion models, which can effectively solve coverage blind spots in complex environments such as urban canyons[15].

From an engineering application perspective, the standardization of multi-base station ISAC systems needs to address hardware heterogeneity and protocol compatibility. The introduction of an open intelligent wireless architecture (O-RAN) enables software-defined sensing functions. Through a hybrid computing architecture of general-purpose processing units (GPUs) and field-programmable gate arrays (FPGAs), it dynamically adapts to sensing requirements in different scenarios[4,6]. Security and privacy protection technologies require collaborative design at both the physical and protocol layers. For example, physical layer security-based sensing signal encryption and federated learning framework-based distributed feature extraction can meet data privacy requirements while ensuring sensing accuracy[15,18]. Breakthroughs in these technical directions will promote the transition of ISAC from theory to large-scale application, providing underlying technical support for scenarios such as low-altitude economy and intelligent transportation.

6. Summary and Outlook

The collaborative sensing technology of multi-base station ISAC breaks through the limitations of single-base station sensing in terms of range, accuracy, and robustness through distributed signal processing and resource fusion, providing technical solutions integrating communication and sensing functions for scenarios such as intelligent transportation and low-altitude economy. Theoretically, its performance is constrained by factors including near /far field propagation models, multipath effects, and time-frequency synchronization accuracy. The technical system covers signal-level collaboration, data-level fusion, and scene-adaptive strategies. Existing research has made systematic progress in parameter estimation frameworks, dynamic topology optimization, NLoS scene adaptation, etc., achieving significant improvements in positioning and velocity estimation accuracy in complex environments.

Current technologies still face challenges in synchronization accuracy, computational complexity, and multi-target interference. Future development will focus on quantum synchronization technology, AI-driven intelligent processing, and heterogeneous network integration. Through theoretical breakthroughs and engineering innovations, it will promote the large-scale application of ISAC technology in 6G and future wireless systems, and build a technical foundation for communication-sensing-control integration in smart city and other scenarios.

Disclosure statement

The author declares no conflict of interest.

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