

RIS-UAV Cooperative ISAC Technology for 6G: Architecture, Optimization, and Challenges

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Abstract

With the development of 6G technology, conventional wireless communication systems are increasingly unable to meet stringent performance requirements in complex and dynamic environments. Therefore, integrated sensing and communication (ISAC), which enables efficient spectrum sharing, has attracted growing attention as a promising solution. This paper provides a comprehensive survey of reconfigurable intelligent surface (RIS)-unmanned aerial vehicle (UAV)-assisted ISAC systems. It first introduces a four-dimensional quantitative evaluation framework grounded in information theory. Then, we provide a structured overview of coordination mechanisms between different types of RIS and UAV platforms within ISAC architectures. Furthermore, we analyze the application characteristics of various multiple access schemes in these systems. Finally, the main technical challenges and potential future research directions are discussed and analyzed.

Keywords: ISAC; RIS; UAV; quantitative evaluation framework

1. Introduction

1.1. Research Background and Motivation

Driven by emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), and virtual reality (VR), future wireless networks are facing unprecedented challenges in terms of spectrum efficiency, energy efficiency (EE), and environmental awareness. According to ITU-R M.2150 and the IMT-2030 technical vision, sixth-generation (6G) networks are expected to support a 10- to 100-fold increase in device connection density compared with 5G, achieve peak data rates of up to 1 Tbps, and deliver user-experienced data rates of 10 Gbps. Meeting these ambitious targets imposes stringent requirements on both communication performance and sensing capability.

To address these challenges, ISAC—by integrating hardware platforms and sharing spectrum resources to support precise sensing and high-rate communication—has been identified as a key technology for 6G and has been explicitly listed by the International Telecommunication Union (ITU) as a critical application scenario [1,2].

Under the 6G vision, ISAC is expected to play an essential role in a wide range of representative use cases. First, in ultra-reliable low-latency communication (URLLC) scenarios such as industrial automation, disaster rescue, and telemedicine, systems must achieve sub-millisecond latency and reliability above 99.999%. In such settings, RIS-UAV-ISAC systems can maintain robust communication links through flexible UAV deployment



Academic Editor: Frank Werner

Received: 1 December 2025

Revised: 19 December 2025

Accepted: 5 January 2026

Published: 12 January 2026

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and intelligent signal reflection while performing environmental sensing during data transmission, thereby significantly enhancing security and real-time performance.

Second, within the space-air-ground integrated network (SAGIN), satellites, UAVs, and terrestrial nodes cooperate to form a unified communication infrastructure. RIS elements can be deployed as intelligent relays on UAV or high-altitude platforms to improve link quality and, when combined with ISAC, provide both emergency communications and environmental perception in disaster scenarios. This architecture extends coverage to remote or disaster-stricken areas.

Finally, in the low-altitude smart IoT (LAS-IoT) scenario, future urban airspace is expected to accommodate large fleets of UAVs performing logistics, public safety, and environmental monitoring tasks. In such environments, the communication system must cope with high user density, strong interference, and numerous dynamic targets.

RIS-UAV-ISAC architectures can enhance the stability of aerial links through RIS-assisted propagation control, while exploiting the three-dimensional (3D) mobility of UAV and the joint sensing and communication capability of ISAC to enable swarm coordination, collision avoidance, and high-precision environmental perception.

Consequently, RIS-UAV-ISAC technology exhibits distinct advantages across key 6G scenarios by providing reliable communication, sensing, and coordination support. These features underpin its potential applications in autonomous driving, smart manufacturing, and smart cities, as illustrated in Figure 1.

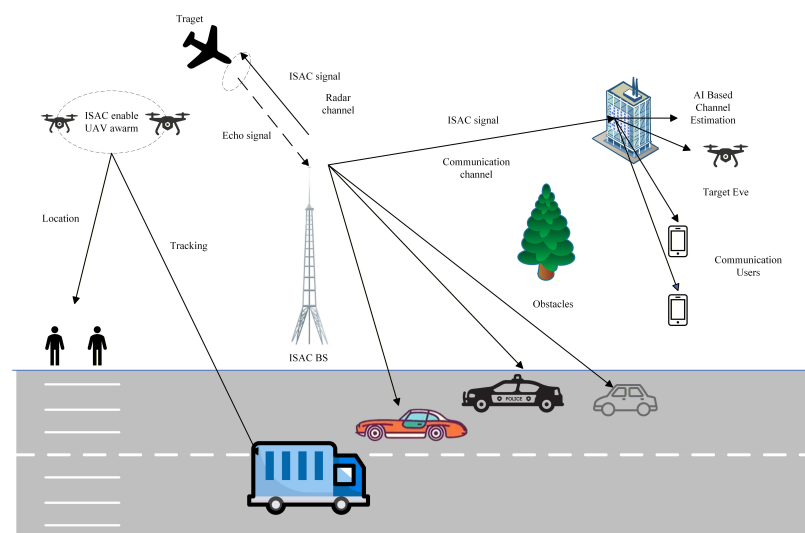


Figure 1. Typical application scenarios of the ISAC system.

1.2. Current Research Status Based on Existing Review Studies

Standardization efforts for ISAC have gained momentum in recent years. The Third Generation Partnership Project (3GPP) has launched preliminary studies on ISAC in Release 19 and plans to further promote its standardization in Release 20. Meanwhile, RIS has been widely recognized as a promising hardware component for 6G networks. By creating virtual line-of-sight (VLoS) channels without requiring direct physical links, RIS can improve the signal-to-noise ratio (SNR), reliability, and communication security.

Existing studies show that RIS-assisted ISAC systems can surpass conventional architectures in both communication and sensing performance [3–8]. However, most current works focus on two-dimensional (2D) terrestrial networks, which fail to fully capture the characteristics of 3D non-terrestrial networks. UAVs, as agile aerial platforms, can operate as temporary base stations (BSs) or relays, significantly enhancing coverage and sensing capabilities in complex environments. They hold strong potential for applications in disaster relief, emergency communications, and air-to-ground (A2G) integrated networks [9].

In parallel, the integration of AI techniques has further advanced ISAC systems. Machine learning and deep reinforcement learning (DRL) techniques enhance target detection accuracy and channel estimation performance while enabling real-time resource optimization in dynamic environments [10–13].

Nevertheless, ISAC systems still face fundamental challenges related to theoretical modeling, system architecture design, and algorithmic complexity. Key issues include the intrinsic contradiction between communication and sensing requirements, the absence of unified performance evaluation metrics, and the limited convergence of traditional optimization methods when dealing with high-dimensional non-convex problems. These challenges introduce both new opportunities and obstacles for the research and practical deployment of RIS-UAV-ISAC systems.

To address the limitations of existing ISAC technologies, this paper conducts an in-depth theoretical and technical study of RIS-UAV collaborative ISAC systems. As summarized in Table 1, research on ISAC has generally evolved through three development stages.

Phase I (2020–2022) [14] focused on systematically classifying ISAC architectures, proposing four configuration models based on the relationship between the BS and the targets and discussing the challenge of reducing hardware cost through system integration. However, the analysis remained largely qualitative, without performance boundary characterization, and it neglected the impact of multi-antenna and large-scale multiple-input multiple-output (MIMO) techniques as well as architecture switching mechanisms in dynamic scenarios.

Phase II (2022–2024) [15] pioneered research on UAV-enabled vehicle-to-everything (V2X) dynamic ISAC beamforming. Although multi-BS cooperation was considered, synchronization overhead was not explicitly addressed. In parallel, ref. [16] investigated the integration of ISAC and non-orthogonal multiple access (NOMA) for next-generation multiple access (MA), covering interference management, power allocation, and beamforming, but provided limited analysis of NOMA in RIS-UAV collaborative scenarios. In addition, ref. [17] explored the combination of ISAC with autonomous driving, intelligent transportation, digital twins, and physical environment perception, and yet the technical depth of this line of work remains limited.

Phase III (2025) [18–20] emphasizes the security aspects of ISAC systems in 6G networks and integrates AI techniques across different application domains. Nevertheless, existing studies mostly stay at the level of listing potential threats, without quantitative risk assessment or in-depth analysis of RIS-UAV integrated architectures. These gaps further motivate the comprehensive investigation presented in this paper.

1.3. Contributions

The main contributions of this paper can be summarized as follows:

- A four-dimensional quantitative evaluation framework for ISAC systems: Building on information theory and related foundations, a four-dimensional quantitative evaluation framework is established. Leveraging this framework, a representative set of surveyed studies are systematically assessed and compared through quantitative analysis.
- A comprehensive survey of RIS-UAV cooperative ISAC architectures: This paper systematically reviews the coordination mechanisms between different types of RIS and UAV, providing a reference for cooperative design in three-dimensional non-terrestrial scenarios. Finally, the core optimization objectives and corresponding solution methodologies are summarized in a tabular form for clarity and comparison.
- An integrated analysis of multiple access techniques in RIS-UAV-ISAC systems: The suitability, advantages, and limitations of advanced multiple access schemes—including

NOMA and RSMA—are systematically examined in the context of RIS-UAV-enabled ISAC.

- Identification of key challenges and future research directions: The paper discusses fundamental open challenges in RIS-UAV cooperative ISAC systems, including communication-sensing tradeoffs, hardware impairments, channel estimation overhead, algorithmic scalability, and security issues. Potential research directions are outlined to guide the development and deployment of next-generation ISAC networks.

The remainder of this paper is organized as follows. Section 1 reviews the development of ISAC technology, summarizes the current state of research, and outlines the main contributions of this work. Section 2 outlines the methods used for the literature search and the criteria applied for study selection. Section 3 presents the mathematical model of the ISAC system and introduces the proposed quantitative evaluation framework. Section 4 describes the integration mechanisms of ISAC, RIS, and UAV, along with the associated multiple access techniques. Section 5 discusses the key challenges and emerging opportunities. Finally, Section 6 concludes the paper.

Table 1. Comprehensive review and comparative analysis of key literature in the ISAC technology field (2022–2025).

Ref.	Year	Main Contribution	RIS-ISAC	UAV-ISAC	RIS-UAV-ISAC	Multi-Access	AI-Driven	Safety Design	System Arch.	Assess. Dim.
[14]	2022	ISAC System Configuration Survey	×	×	×	*	×	*	✓	2
[15]	2024	Collaborative multi-BS ISAC	×	×	*	✓	*	✓	✓	3
[16]	2024	ISAC and NOMA Integration	*	×	×	✓	*	✓	*	2
[17]	2024	Multi-dimensional Perception Capabilities of ISAC	×	*	*	×	*	*	✓	2
[18]	2025	Overview of the ISAC Layered Architecture	*	*	×	✓	*	✓	✓	3
[19]	2025	6G Network ISAC Safety Vision	✓	×	*	*	✓	✓	✓	3
[20]	2025	6G ISAC Enabling Technologies	✓	*	×	✓	✓	✓	✓	3
This article	2025	RIS-UAV Collaborative ISAC	✓	✓	✓	✓	✓	✓	✓	4

Note: × Not Covered; * Partially Covered; ✓ Fully Covered.

2. Literature Review Methodology

This study conducts a systematic literature review to identify relevant publications. Searches were performed in IEEE Xplore, Scopus, Web of Science, PubMed, and CNKI using keyword groups related to ‘Integrated Sensing and Communication, Joint Communication and Sensing, Communication Sensing Integration, ISAC, JCAS’, ‘Reconfigurable Intelligent Surface, Intelligent Reflecting Surface, RIS, IRS’, ‘Trajectory Optimization, Path Planning, Mobility Management’, and ‘Beamforming, Beam Forming, Beam-Steering’. This process yielded 540 records.

Studies were included if they addressed ISAC, RIS, or UAV technologies. Works limited to mathematical derivations without clear practical relevance were excluded, as were duplicate publications or those with more than 80% overlap with included studies.

For each eligible study, the technical approach, performance metrics, simulation settings, and main contributions were extracted. The screening and quality assessment followed the PRISMA framework in Figure 2, resulting in 110 included publications, whose publication trends are summarized in Figure 3.

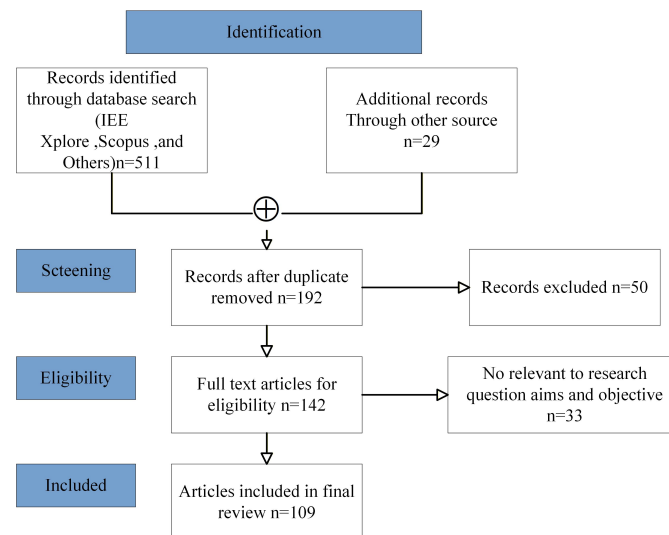


Figure 2. PRISMA flow diagram for study identification and selection.

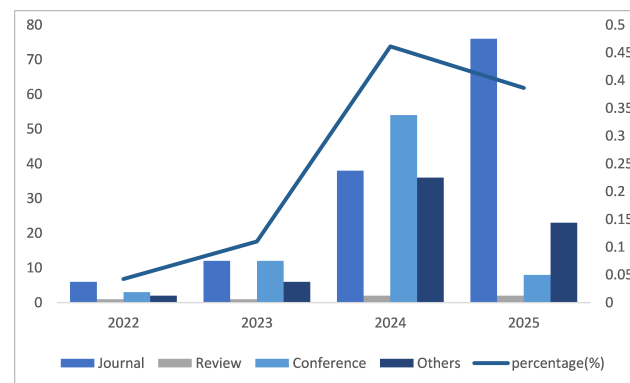


Figure 3. The development of ISAC-related publications.

3. ISAC Foundation and Evaluation Framework

The abbreviations used throughout this paper are summarized in the Abbreviations section.

ISAC enables the realization of communication and sensing functionalities using a shared waveform, spectrum resources, and hardware infrastructure, thereby achieving high spectral efficiency and strong system scalability. This section first introduces the fundamental physical layer model of ISAC systems and then presents an information-theoretic four-dimensional quantitative evaluation framework.

3.1. Physical Layer Model of ISAC Systems

Consider a multiple-input multiple-output (MIMO)-ISAC system equipped with N_t transmit antennas and N_r receive antennas, which simultaneously serve K communication users and detect P sensing targets. The corresponding system model is illustrated in Figure 4.

Figure 4 illustrates a common ISAC system model that serves as a conceptual baseline for the surveyed architectures throughout this paper.

In this model, a base station (BS) simultaneously transmits downlink communication signals to multiple users and radar signals toward sensing targets using shared spectrum and waveform resources. The communication links are represented by the downlink signal paths from the BS to users, while the sensing functionality is realized through radar signal transmission and echo reception from targets.

Communication channel model:

In the downlink of a MIMO-ISAC system, the signal received by the k -th communication user can be expressed as Equation (1) [1].

$$y_k(t) = \mathbf{h}_k^H \mathbf{W} \mathbf{s}(t) + n_k(t), \quad (1)$$

where $\mathbf{h}_k \in \mathbb{C}^{N_t \times 1}$ denotes the channel vector from the BS to user k , $\mathbf{W} \in \mathbb{C}^{N_t \times K}$ is the precoding matrix, $\mathbf{s}(t) \in \mathbb{C}^{K \times 1}$ is the transmit signal vector for the K users, and $n_k(t) \sim \mathcal{CN}(0, \sigma^2)$ denotes the additive white Gaussian noise.

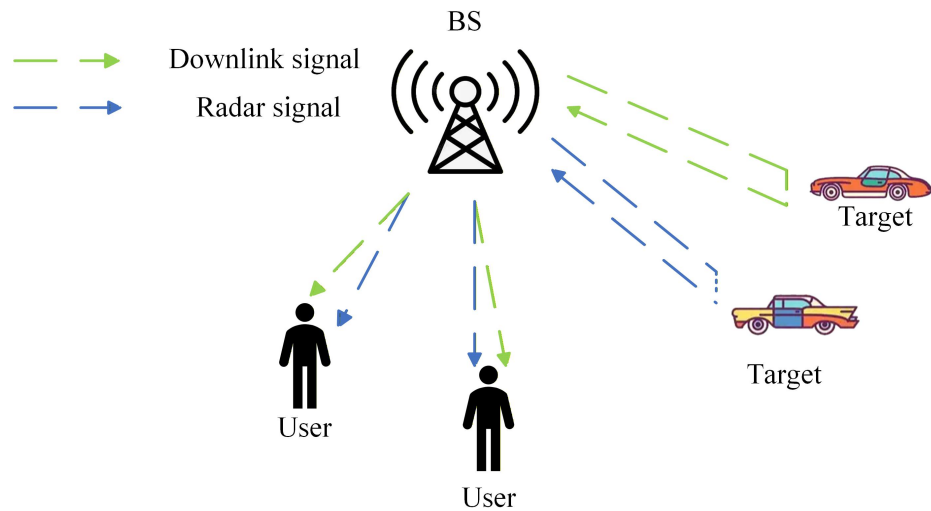


Figure 4. ISAC system model.

Sensing model:

In the sensing subsystem, the received echo signal can be written as Equation (2) [21].

$$\mathbf{y}_r = \sum_{l=1}^L \xi_l \mathbf{a}_r(\theta_l) \mathbf{a}_t^H(\theta_l) \mathbf{X} + \mathbf{Z}_r, \quad (2)$$

where ξ_l is the scattering coefficient of the l -th target, $\mathbf{a}_r(\theta_l)$ and $\mathbf{a}_t(\theta_l)$ denote the receive and transmit array response vectors corresponding to angle θ_l , respectively, $\mathbf{X}$ is the transmit signal matrix, and $\mathbf{Z}_r$ denotes the receiver noise matrix.

Although ISAC provides an efficient mechanism for jointly supporting communication and sensing, practical deployments in complex environments still suffer from channel fading, self-interference, and high energy consumption. The introduction of RIS and UAV provides additional spatial and electromagnetic degrees of freedom, enabling further performance enhancement. These extensions are discussed in detail in the subsequent sections.

3.2. Four-Dimensional Evaluation Framework for ISAC System Performance Assessment Based on Information Theory

To enable a systematic and fair performance comparison of RIS-UAV-ISAC systems, this paper proposes a four-dimensional quantitative evaluation framework grounded in information theory, statistical estimation theory, and optimization theory. The four metrics capture complementary yet interrelated performance aspects, thereby reflecting the practical requirements of future 6G networks.

3.2.1. Communication Performance Indicators

Communication rate is a fundamental metric that quantifies the amount of information that can be reliably transmitted per unit time. It directly reflects the effective data throughput of ISAC systems.

Based on Shannon's capacity theory, the achievable rate of user k can be written as Equation (3) [1].

$$R_k = \log_2(1 + \text{SINR}_k), \quad (3)$$

where SINR_k denotes the signal-to-interference-plus-noise ratio (SINR) of user k .

When a RIS is introduced, the channel becomes a cascaded BS-RIS-user link, and the SINR expression can be written as Equation (4).

$$\text{SINR}_k = \frac{|\mathbf{h}_k^H \mathbf{G} \mathbf{w}_k|^2}{\sum_{j \neq k} |\mathbf{h}_k^H \mathbf{\Theta} \mathbf{G} \mathbf{w}_j|^2 + \sigma_k^2}, \quad (4)$$

where $\mathbf{\Theta} = \text{diag}(e^{j\theta_1}, \dots, e^{j\theta_N}) \in \mathbb{C}^{N \times N}$ is the RIS phase-shift matrix, $\mathbf{G}$ denotes the BS-RIS channel, $\mathbf{w}_k$ is the beamforming vector for user k , and σ_k^2 represents the noise power.

3.2.2. Perceptual Performance Metrics

Sensing performance is characterized using the Cramér-Rao bound (CRB), which provides a theoretical lower bound on the variance of any unbiased estimator. The CRB is widely adopted to quantify estimation accuracy for target parameters such as distance and angle [21].

The CRB can be expressed as Equation (5).

$$\text{CRB}(\boldsymbol{\xi}) = [\mathbf{J}(\boldsymbol{\xi})]^{-1}, \quad (5)$$

where $\boldsymbol{\xi} = [\theta_r, \phi_r, \rho_r, \tau_r]^T$ denotes the vector of unknown target parameters, and $\mathbf{J}(\boldsymbol{\xi})$ is the Fisher information matrix (FIM) with entries Equation (6).

$$[\mathbf{J}(\boldsymbol{\xi})]_{i,j} = -\mathbb{E} \left[\frac{\partial^2 \ln p(\mathbf{y} | \boldsymbol{\xi})}{\partial \xi_i \partial \xi_j} \right], \quad (6)$$

where $p(\mathbf{y} | \boldsymbol{\xi})$ is the likelihood function of the received signal $\mathbf{y}$. For target parameters $\boldsymbol{\xi}$ (including angle-of-arrival, radar cross section, etc.), the CRB, thus, specifies the minimum achievable estimation error for unbiased estimators, which can be asymptotically attained under high SNR conditions [22].

3.2.3. Resource Efficiency Indicators

EE measures the total achievable communication rate per unit of power consumption. In a conventional ISAC system, the power consumption is dominated by the BS transmit power, and EE is defined as the ratio of the total communication rate to the total power consumption. However, when RIS and UAV are incorporated, the overall power consumption increases to $P = P_{\text{tx}} + P_{\text{RIS}} + P_{\text{UAV}}$, and the EE expression becomes Equation (7).

$$\eta_{\text{EE}} = \frac{\sum_{k=1}^K R_k}{P_{\text{tx}} + P_{\text{RIS}} + P_{\text{UAV}}}, \quad (7)$$

where P_{tx} denotes the BS transmit power, P_{RIS} represents the power consumed by the RIS, and P_{UAV} is the propulsion- and communication-related power consumption of the UAV.

3.2.4. System Complexity Indicators

Algorithmic complexity is characterized using big- O notation, $O(f(n))$, which reflects the computational resources required by an algorithm [14], where n denotes the problem size (e.g., number of antennas, number of users, etc.). The complexities of several typical optimization algorithms are summarized in Table 2.

Table 2. Comparison of typical optimization algorithm complexities.

Algorithm Type	Complexity	Typical Execution Time	Representative Scenarios
Convex optimization	$O(n^3)$	Second-level	Small-scale static problems
Alternating optimization (AO)	$O(In^2)$	Minute-level	Medium-scale optimization
Deep learning (DL) inference	$O(LH^2)$	Millisecond-level	Large-scale dynamic environments
Federated learning (FL)	$O(Mn^2)$	Hourly-level	Distributed learning scenarios

Note: I = number of iterations, n = problem size (e.g., antennas, users), L = number of network layers, H = number of hidden units, M = number of devices.

All performance metrics are normalized with respect to a baseline ISAC system without RIS. The normalization is given by

$$\eta_{\text{norm}} = \frac{\eta_{\text{scheme}}}{\eta_{\text{baseline}}}, \quad (8)$$

where η_{scheme} and η_{baseline} denote the performance metric of the considered scheme and the baseline ISAC system, respectively.

3.3. Chapter Summary

This chapter establishes the theoretical foundation and analytical basis for the survey of RIS-UAV-ISAC systems. It first introduces a unified physical layer model for ISAC, providing a common reference for different ISAC architectures. Based on this model, a four-dimensional quantitative evaluation framework is presented to systematically assess communication performance, sensing accuracy, resource efficiency, and system complexity. By adopting normalized metrics and a unified analytical perspective, this framework enables a consistent comparison of different ISAC studies and lays a solid foundation for the architectural and technological analyses in the subsequent chapters.

4. RIS and UAV Enabling Technologies

RIS and UAV can each exploit their unique advantages to collaborate with ISAC, delivering performance improvements that exceed those of standalone ISAC systems. This section introduces ISAC architectures enhanced through RIS and UAV integration.

4.1. RIS-Assisted ISAC System

RIS is composed of a large number of programmable elements that can manipulate the propagation of incident electromagnetic waves by adjusting their phase and amplitude. They provide a low-cost, low-power approach for environment-aware reconfiguration in ISAC systems. According to their hardware characteristics and implementation methods, RIS-assisted ISAC architectures can be broadly classified into the following four categories.

4.1.1. Passive RIS-Assisted ISAC System

The block diagram of a passive RIS (PRIS)-assisted ISAC system is shown in Figure 5. In this architecture, the RIS establishes a cascaded BS-RIS-user link, enabling VLoS paths for both communication and sensing signals, and the RIS performs reflective beamforming

by adjusting the phase shifts in its individual elements. The corresponding reflection coefficient matrix can be expressed as Equation (9).

$$\Theta_{\text{passive}} = \text{diag}(e^{j\theta_1}, \dots, e^{j\theta_N}), \quad \theta_n \in [0, 2\pi) \quad (9)$$

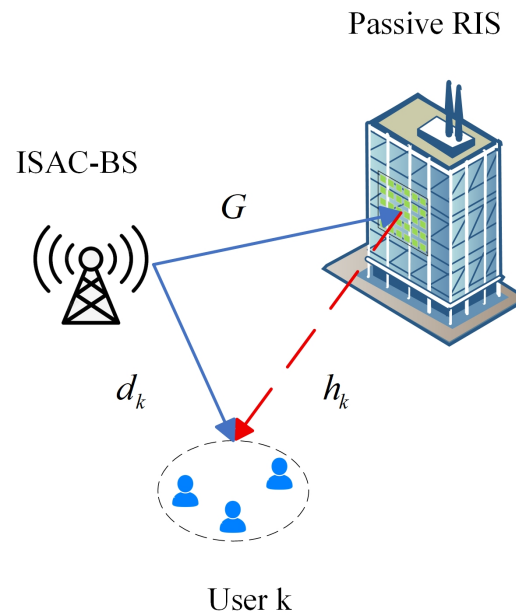


Figure 5. Passive RIS-assisted ISAC system.

PRIS features low power consumption and requires no radio-frequency (RF) chains, providing a solid foundation for enhancing system performance. In the context of RIS-assisted localization, existing studies have mainly followed three technical routes. Reference [23] proposes a passive sensing scheme based on distributed semi-PRIS deployment, which eliminates the need for dedicated positioning reference signals in conventional localization methods and achieves millimeter-level positioning accuracy for multiple users. However, although this approach avoids explicit channel state information (CSI) acquisition, further improving localization accuracy requires deploying additional sub-RISs, leading to a significant increase in cost and implementation complexity. To address this issue, ref. [24] innovatively exploits the inherent location information contained in communication signals received from users in RIS blind zones under imperfect CSI conditions, thereby enabling fine-grained localization without increasing the number of RISs. In another line of work, ref. [25] derives the radar SNR metric for target detection and the CRB for angle-of-arrival estimation. Under limited resource constraints, this approach not only improves localization performance but also provides a better tradeoff between communication and sensing.

Although RIS can enhance signal coverage and strength by adjusting the reflection angle and amplitude of beamforming signals—thereby improving the wireless propagation environment and sensing accuracy—the information of signals is simultaneously exposed to the sensed targets. As a result, adversaries equipped with advanced receivers may exploit these signals to eavesdrop on sensitive communications [26].

References [27,28] investigate the use of RIS to enhance physical layer security (PLS) and ISAC performance from different perspectives. In [27], random phase perturbations are introduced into the RIS configuration to deliberately degrade sensing accuracy, injecting interference into both the magnitude and phase of the CSI and thereby weakening an eavesdropper's ability to reliably infer user data. Similarly, ref. [29] exploits imperfect

sensing estimates and employs dedicated radar signals as artificial noise (AN), making it difficult for eavesdroppers to acquire accurate CSI and indirectly improving PLS.

In [30], the authors focus on EE optimization for multi-user, multi-target systems with partially blocked direct links. Reference [31] proposes a RIS-assisted sensing-aided communication enhancement (R-SACE) mechanism to improve the communication performance of ISAC systems in practical scenarios with imperfect CSI. Reference [32] employs RIS in an ISAC system to mitigate multi-user interference (MUI) while preserving the desired radar sensing beam pattern. In [33], the authors propose a unified signal model for RIS-assisted ISAC systems and jointly design the transmit waveform, receive filter, and passive beamforming. Building on this, ref. [28] further investigates the problem of maximizing the communication sum rate subject to a worst-case radar output SNR constraint.

Although PRIS can effectively enhance communication quality and sensing accuracy through its simple architecture and ultra-low power consumption, its performance is fundamentally constrained by multiplicative fading, two-hop path loss, and the high overhead associated with channel estimation.

The channel loss of a PRIS-assisted link can be expressed as Equation (10).

$$PL_{\text{passive}} = \left(\frac{4\pi d_1}{\lambda} \right)^{\alpha_1} \left(\frac{4\pi d_2}{\lambda} \right)^{\alpha_2}, \quad (10)$$

where d_1 and d_2 denote the distances between the BS and RIS, and between the RIS and the user, respectively, and α_1 and α_2 are the corresponding path-loss exponents.

As indicated by Equation (10), passive reflection is unable to compensate for the inherent path loss accumulated along the two-hop propagation path. However, with the development of active RIS (ARIS) technologies, new solutions have emerged that can overcome these performance bottlenecks imposed by physical limitations.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 3.

4.1.2. Active RIS-Assisted ISAC System

ARIS incorporates controllable gain amplifiers that not only provide phase modulation but also enhance the amplitude of reflected signals, thereby compensating for severe fading in cascaded links and extending communication and sensing coverage. However, the use of active elements also introduces additional noise and increased power consumption, resulting in extra system overhead [34].

A typical system model is illustrated in Figure 6, where the RIS is equipped with active elements capable of both phase adjustment and signal amplification.

As shown in Figure 6, the amplified reflected signals enhance communication coverage and sensing accuracy, especially in long-distance or blocked scenarios. However, the use of active components also introduces additional noise and power consumption, leading to new tradeoffs between performance and EE.

The active RIS reflection matrix is given by Equation (11).

$$\mathbf{\Theta}_{\text{active}} = \text{diag}(\beta_1 e^{j\theta_1}, \dots, \beta_N e^{j\theta_N}), \quad (11)$$

where $\beta_n \leq \beta_{\max}$ denotes the power amplification gain of the n -th element and $\theta_n \in [0, 2\pi)$ is its phase shift.

Current research has investigated the role of ARIS in ISAC systems from several complementary perspectives. In [35], an ARIS-assisted secure ISAC framework is proposed to support multi-user communication and eavesdropper detection, where the secrecy rate (SR) is optimized under radar signal-to-interference-plus-noise ratio constraints. However,

this work does not account for the noise and interference introduced by ARIS elements. Reference [36] addresses this limitation by explicitly considering amplifier noise and interference, demonstrating that ARIS can further enhance SR performance in single-target detection scenarios.

Table 3. Summary of optimization objectives and methods for representative PRIS-ISAC schemes.

Ref.	System Model	Optimization Objective	Method
[23]	PRIS-ISAC	Maximize the sum rate over ISAC and passive sensing (PC) periods	Two novel beamforming for joint ISAC/PC operation
[24]	PRIS-ISAC	Maximize communication rate and fine-grained localization accuracy	Sensing-assisted communication (SSC) using inherent location information in signals received from users in RIS blind zones
[25]	PRIS-ISAC	Maximize the achievable sum rate of multi-user communication under target detection SNR or parameter-estimation CRB constraints, transmit power budget, and unit-modulus RIS coefficients	Fractional programming (FP), majorization-minimization (MM), and alternating direction method of multipliers (ADMM)
[27]	PRIS-ISAC	Degrade sensing accuracy by introducing random phase increments in the IRS layout for adversarial protection	Novel physical-layer adversarial sensing countermeasure based on random phase perturbation
[28]	PRIS-ISAC	Jointly design BS transmit beamforming, receive filter, and RIS reflection coefficients to maximize the sum rate while satisfying worst-case radar output SNR, transmit power, and unit-modulus constraints	FP, MM, and ADMM
[29]	PRIS-ISAC	Maximize the sum secrecy rate subject to users' Quality of Service (QoS) constraints, transmit power limits, and sensing signal-strength requirements	S-procedure and deterministic-equivalent transformation
[30]	PRIS-ISAC	Maximize EE	Alternating optimization (AO)
[31]	PRIS-ISAC (R-SACE)	Jointly optimize temporal and spatial resources under probabilistic, sensing performance, transmit power, and interference constraints to maximize average system throughput (AST) of the R-SACE mechanism	Fixed-point iteration (FPI)
[32]	PRIS-ISAC	Jointly optimize Dual-functional radar and communication (DFRC) waveform and RIS phase-shift matrix to minimize MUI under stringent beam pattern constraints	Manifold-optimization-based AO
[33]	PRIS-ISAC	Jointly design dual-functional transmit waveform and RIS passive beamforming to maximize radar output SINR achieved via space-time adaptive processing (STAP)	ADMM combined with MM

In [37], an ARIS-assisted ISAC system is studied, where the additional degrees of freedom (DoF) provided by active elements are exploited to improve overall system performance. The authors derive, for the first time, the CRB for target parameter estimation and develop a joint beamforming algorithm to minimize estimation error. Reference [38] formulates two EE maximization problems for subcarrier-based ARIS (SC-ARIS)-assisted systems and proposes corresponding joint beamforming optimization schemes.

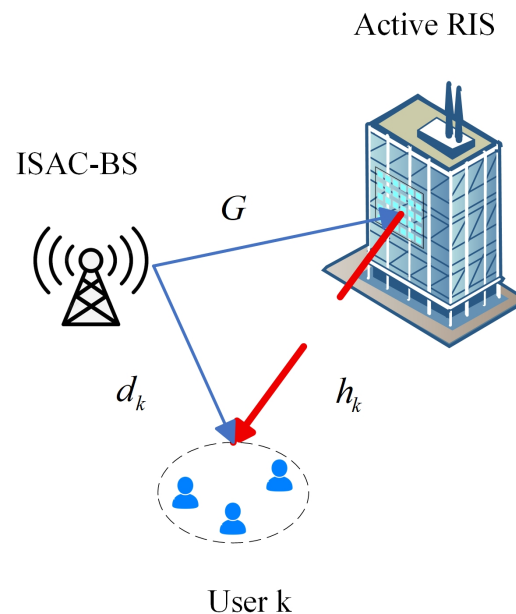


Figure 6. Active RIS-assisted ISAC system model.

ARIS also shows significant potential for radar sensing enhancement. Reference [39] develops a comprehensive signal model for RIS-assisted radar and analyzes its capability to improve target detectability. In [40], a sensor-assisted ARIS architecture is introduced, where signal amplification from active RIS elements strengthens sensor measurements, and onboard sensing eliminates the need for echo signals to return to the BS, thus enabling simultaneous data transmission and target perception. Moreover, ref. [41] proposes an SC-ARIS with a fully connected hybrid precoding (HP) structure, allowing multiple RIS elements to share a single power amplifier. This design maximizes EE while maintaining communication and sensing performance, providing useful insights for scenarios with imperfect eavesdropper CSI. Reference [42] presents a novel multi-perspective observation framework that integrates symbol-level precoding (SLP) with STAP, utilizing multiple ARIS panels to achieve target-clutter separation and significantly improve detection accuracy. Finally, ref. [43] investigates transmit power allocation and active RIS deployment strategies when a moderate number of reflecting elements are available.

However, both passive RIS and active RIS architectures suffer from limited channel estimation accuracy in practical deployment scenarios. To overcome the respective shortcomings of fully passive and fully active designs, a hybrid RIS (HRIS) architecture has been proposed, which integrates the advantages of both technologies to achieve a more reliable and flexible system performance.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 4.

Table 4. Summary of optimization objectives and methods for representative ARIS-ISAC schemes.

Ref.	System Model	Optimization Problem	Method
[34]	ARIS-ISAC	Maximize the minimum beam pattern gain in the target direction subject to secure transmission, power budget, active RIS reflection coefficient, and active RIS-induced noise constraints	AO with penalty-enhanced successive convex approximation (SCA)
[35]	ARIS-ISAC	Jointly design radar receive beamformer, active RIS reflection coefficient matrix, and transmit beamformer to maximize the achievable secrecy rate	FP and MM
[36]	ARIS-ISAC	Jointly design the DFRC BS beamforming matrix and active RIS reflection coefficients to maximize the system SR	AO algorithm based on semidefinite relaxation (SDR) and MM
[37]	ARIS-ISAC	Maximize radar output SNR while guaranteeing predefined SINR requirements at communication users	Block coordinate descent (BCD), Dinkelbach's transformation, and MM
[38]	ARIS-ISAC	Joint beamforming design to maximize EE in a sub-connected active RIS architecture	The EE structure of sub-connected ARIS
[39]	ARIS-ISAC	Maximize SINR subject to practical waveform constraints and discrete RIS phase shifts	AO within an MM
[40]	ARIS-ISAC	Maximize the SNR of target echo signals at a sensor array subject to communication quality, power budget, and RIS amplification constraints	Iterative SCA
[41]	ARIS-ISAC	Jointly design DFBS hybrid precoder and SC-ARIS beamforming to maximize secure EE while guaranteeing communication and sensing quality	AO combined with manifold-optimization-based alternating minimization and SDR
[42]	ARIS-ISAC	Joint design of transmit waveform, reflection coefficients of multiple active RISs, and space-time receive filter to maximize radar signal-to-clutter-plus-noise ratio (SCNR) for target detection under user QoS constraints	AO with FP, MM, and ADMM
[43]	ARIS-ISAC	Maximize radar SINR subject to QoS constraints of communication users and transmit power limits at active RIS and DFRC BS	MM combined with SDR
[44]	ARIS-ISAC	Joint design of transmit beamforming, DFA-RIS configuration, and reflection amplifier (RA) modes to maximize EE of a DFA-RIS-assisted multi-user MISO system under perfect and imperfect CSI	AO with penalty dual decomposition (PDD) and AO with constrained stochastic MM (CSMM)

4.1.3. HRIS-Assisted ISAC System

HRIS combines both passive and active elements, as illustrated in Figure 7. Each reflecting unit in the HRIS can operate in two modes. In the active mode, the element provides signal amplification to compensate for propagation path loss, which is suitable for

communication scenarios requiring high signal quality. In the passive mode, the element only adjusts the phase of the incident signal to improve transmission quality without additional power consumption [45]. In this way, the HRIS can offer gain compensation on critical links while preserving high EE.

Here, Θ_a denotes the active phase-shift matrix, and Θ_p represents the passive phase-shift matrix of the HRIS.

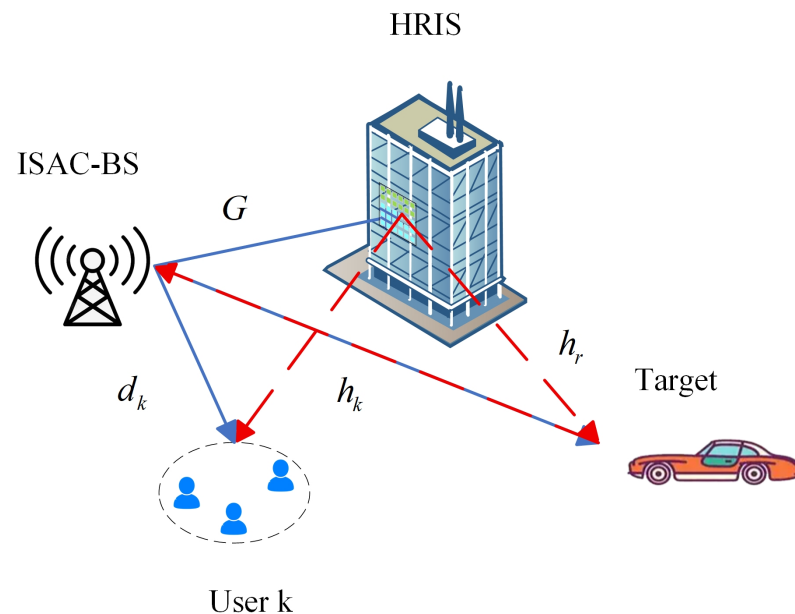


Figure 7. HRIS-assisted ISAC system.

Reference [45] investigates a joint RIS mode selection and beamforming design problem in ISAC systems, aiming to maximize the minimum sensing beam gain of the target. In [46], a distributed HRIS-assisted V2X-ISAC architecture is proposed, where a pre-designed transmission protocol is employed to achieve high ISAC performance with low complexity and reduced channel estimation overhead under time-varying channels. Reference [47] reviews the bidirectional controllability of HRIS, which enables both the controlled reflection of incident signals and target sensing and discusses how these sensing capabilities can be exploited to enhance network management.

In [48], a novel security strategy and target detection scheme is presented to enable simultaneous secure downlink communication and target detection. Similarly, ref. [49] proposes a communication-centric security framework that leverages the dual-function capability of HRIS to support joint dual-base sensing and secure downlink transmission. Furthermore, ref. [50] introduces a semi-self-sensing HRIS (SS-HRIS) operating in the terahertz (THz) band, which helps mitigate severe multipath fading in THz channels and achieves a high aggregate data rate.

HRIS offers promising advantages in balancing coverage and EE; however, its system design complexity and inherent half-space coverage limitation can significantly constrain overall performance. To address these bottlenecks, ref. [51] proposes an innovative architecture that enables simultaneous transmission and reflection, thereby achieving full-space coverage.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 5.

Table 5. Summary of optimization objectives and methods for representative HRIS-ISAC schemes.

Ref.	System Model	Optimization Problem	Method
[45]	HRIS-ISAC	Maximize the minimum beam pattern gain among multiple targets by jointly optimizing BS transmit beamforming, mode selection of each HRIS element, and HRIS reflection coefficient matrix	AO, SCA, and SDR
[46]	HRIS-ISAC	Improve ISAC performance while minimizing channel estimation overhead and algorithmic complexity	Distributed HRIS architecture
[48]	HRIS-ISAC	Maximize the worst-case sensing SINR subject to secure communication and power budget constraints	Generalized fractional programming (GFP) and PDD
[49]	HRIS-ISAC	Joint optimization of BS precoding and HRIS reflection/analog-combining configuration to accurately estimate legitimate users and eavesdroppers while ensuring secrecy spectral efficiency requirements	Novel secrecy-constrained ISAC problem formulation with joint HRIS-precoder optimization
[50]	HRIS-ISAC	Joint BS beamforming and HRIS precoding to maximize the sum rate of communication users while maintaining satisfactory sensing performance measured by the CRB	Deep deterministic policy gradient (DDPG)

4.1.4. STAR-RIS-Assisted ISAC System

Simultaneous transmission and reflection intelligent surfaces (STAR-RISs) are a new type of wireless environment control technology composed of programmable elements that can independently adjust the phase and amplitude of both transmitted and reflected signals, thereby offering greater control flexibility. The corresponding system model is shown in Figure 8, where the STAR-RIS is capable of simultaneously transmitting and reflecting signals. Unlike conventional RIS, STAR-RIS provides full-space coverage by serving users and sensing targets located on both sides of the surface. This capability significantly enhances deployment flexibility and spatial degrees of freedom for ISAC systems in dense or complex environments.

Figure 9 highlights the fundamental difference between reflection-only operation and simultaneous transmission and reflection. The comparison clarifies why STAR-RIS can overcome the half-space coverage limitation inherent to traditional RIS architectures.

The transmission and reflection coefficient matrices of the STAR-RIS are given, respectively, by Equations (12) and (13).

$$\mathbf{\Theta}_t = \text{diag}\left(\sqrt{\beta_{t,1}} e^{j\theta_{t,1}}, \dots, \sqrt{\beta_{t,N}} e^{j\theta_{t,N}}\right), \quad (12)$$

$$\mathbf{\Theta}_r = \text{diag}\left(\sqrt{\beta_{r,1}} e^{j\theta_{r,1}}, \dots, \sqrt{\beta_{r,N}} e^{j\theta_{r,N}}\right), \quad (13)$$

where $\beta_{t,n}$ and $\beta_{r,n}$ denote the power allocation coefficients for transmission and reflection, respectively, and $\theta_{t,N}$ and $\theta_{r,N}$ represent the corresponding phase shifts.

STAR-RIS overcomes the half-space coverage limitation of conventional RIS and can provide substantial communication and sensing gains in multi-user, multi-target environments. Reference [52] studies a STAR-RIS-assisted ISAC system in which the service area is partitioned into dedicated sensing and communication zones and derives the CRB for estimating the 2D direction of arrival (DoA) of targets. Building on this work,

ref. [53] installs dedicated sensors on both sides of the STAR-RIS to enable full-space target sensing and proposes a time-switching (TS) protocol for uplink target sensing and communication in both the reflection and transmission regions. Reference [54] investigates an energy-splitting (ES)-based STAR-RIS-enabled ISAC network and formulates a sensing SNR maximization problem.

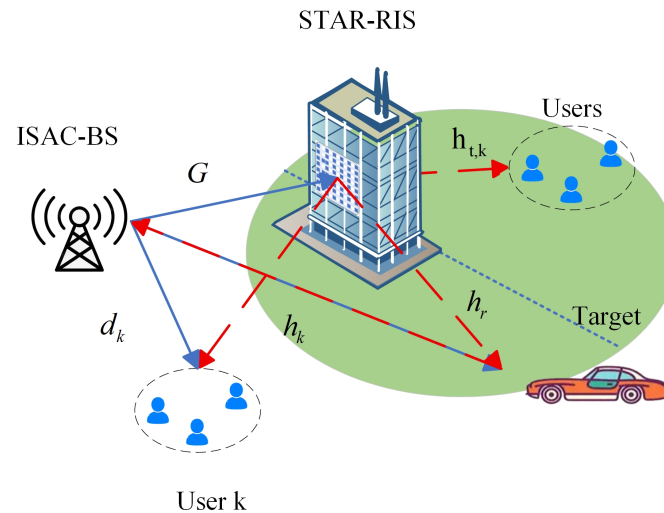


Figure 8. STAR-RIS-assisted ISAC system.

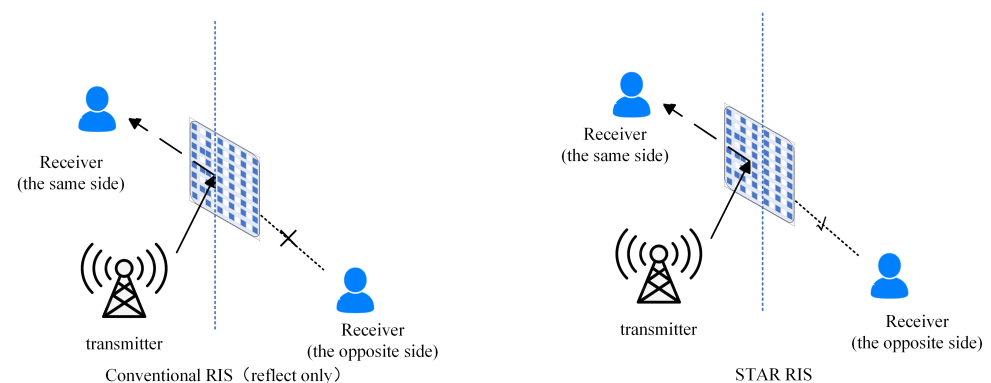


Figure 9. Comparison between STAR-RIS and conventional RIS.

In [55], an ISAC system for the Internet of Everything is considered, jointly analyzing communication and sensing performance under communication-enhanced and communication-sensing fusion scenarios. This work also introduces AN under imperfect CSI to improve communication security. Reference [56] focuses on STAR-RIS-assisted secure ISAC networks under various malicious attacks and proposes a joint PLS and covert communication strategy that balances radar sensing and secure transmission. In [57], an energy-sharing-based STAR-RIS-assisted MIMO system is examined, and a suboptimal block coordinate descent algorithm is developed to jointly design the precoding matrices and STAR-RIS coefficients.

For high-mobility millimeter-wave scenarios, ref. [58] leverages STAR-RIS to enhance communication services for in-vehicle user equipment (UE), while nearby roadside units (RSUs) are employed for vehicle positioning and velocity estimation. Reference [59] proposes a dynamic scatterer tracking scheme using an active STAR-RIS that can simultaneously receive and further process incident signals from both sides, thereby reducing training overhead and improving transmission performance. It also investigates covert communication in millimeter-wave ISAC networks with STAR-RIS under imperfect CSI, where the

antenna array is split into two parts: one dedicated to single-target sensing and the other to covert communication, yielding improved sensing and communication performance.

Moreover, ref. [60] introduces active STAR-RIS into ISAC systems to synthesize high-quality radar beam patterns while satisfying covertness and security constraints. Reference [61] enhances system efficiency and coverage while protecting communication against multiple eavesdroppers. Finally, ref. [62] tests a robust security-energy efficiency design under target angle estimation uncertainty, jointly optimizing communication and sensing performance.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 6.

Table 6. Summary of optimization objectives and methods for representative STAR-RIS-assisted ISAC schemes.

Ref.	System Model	Optimization Problem	Method
[52]	STAR-RIS-ISAC	Minimize the CRB while satisfying minimum communication requirements	PDD
[53]	STAR-RIS-ISAC	Minimize the CRB of the 2D DoA estimation	AO and standard semidefinite programming (SDP)
[54]	STAR-RIS-ISAC	Joint optimization of BS transmit beamforming and STAR-RIS transmission/reflection beamforming to maximize sensing SNR	SDR, MM, and sequential rank-one constraint relaxation
[55]	STAR-RIS-ISAC	Joint optimization of BS beamforming and STAR-RIS phase shifts to improve robust symbol error rate (SER)	FP, AO, iterative SDR, SCA, and S-procedure
[56]	STAR-RIS-ISAC	Joint design of BS transmit beamformer, receive filter, and active STAR-RIS transmit/reflect beamforming to maximize average sum secrecy and covert rates	SCA, SDR, and sequential rank-one constraint relaxation
[57]	STAR-RIS-ISAC	Maximize weighted sum rate based on an ES protocol	BCD and concave-convex procedure (CCCP)
[58]	STAR-RIS-ISAC	Joint extraction of cascaded channel parameters from multiple RSUs to achieve vehicle positioning and velocity estimation	Multi-dimensional orthogonal matching pursuit (MOMP)
[59]	STAR-RIS-ISAC	Simultaneous indoor UE communication and outdoor dynamic scatterer sensing and tracking	Target mismatch detection + path-conflict prediction mechanisms
[60]	STAR-RIS-ISAC	Achieve high-quality radar beam patterns under joint covertness and security constraints	AO + SDR
[61]	STAR-RIS-ISAC	Joint optimization of BS beamforming, STAR-RIS transmit/reflect coefficients, and receive filter to maximize long-term average secrecy rate for all legitimate users	DDPG and SAC
[63]	STAR-RIS-ISAC	Joint optimization of Alice's transmit beamforming and STAR-RIS transmit/reflect coefficients to maximize covert rate	S-procedure + generalized positive semidefinite formulation

4.1.5. Application of Multiple Access Techniques in RIS-ISAC Systems

Since communication and sensing signals are superimposed in ISAC systems, researchers have explored the integration of ISAC with advanced multiple access (MA) techniques—such as NOMA and rate-splitting multiple access (RSMA)—both of which rely on successive interference cancellation (SIC) for signal decoding [64].

NOMA superposes multi-user communication signals and sensing signals in the power domain at the transmitter, and employs SIC at the receiver to suppress inter-user interference (IUI) and interference from sensing signals. Reference [65] exploits NOMA-based SIC to mitigate user interference and, under underloaded conditions, provides greater flexibility for radar detection, thereby effectively enhancing sensing power. In [66], RIS is jointly designed with NOMA, where RIS improves line-of-sight (LOS) connectivity and NOMA enables spectrum-efficient multi-user access; this combination effectively mitigates the impact of imperfect CSI at the eavesdropper side and enhances system robustness. Building on this idea, ref. [67] utilizes the receiver's prior knowledge of the sensing signal and applies SIC-based reception together with RIS, further improving radar detection performance.

Furthermore, ref. [68] considers a RIS-assisted ISAC system that simultaneously serves multiple users and senses multiple targets. By integrating NOMA's power-domain multiplexing with SIC, the system achieves significantly higher spectral efficiency while reducing IUI. At a broader level, the full-duplex cooperative NOMA (C-NOMA) framework proposed in [69] enables multiple users to share the same time-frequency resources while mitigating severe inter-cluster interference. When combined with RIS, this framework extends coverage, suppresses interference, and improves signal quality.

RSMA partitions each user's message into a common part and a private part. The common parts of all users are combined into a single common stream, encoded, and transmitted together with the individual private streams. At the receiver, SIC is employed to decode first the common stream and then the private streams. In this way, interference is partly decoded via the common stream and partly treated as noise, enabling flexible interference management. RSMA is a generalized multiple access scheme that includes conventional space-division multiple access (SDMA) and NOMA as special cases.

Reference [70] proposes an RSMA-enabled ISAC system to manage interference between radar and communication functions as well as among users. By exploiting the RSMA common stream to replace conventional radar probing sequences while simultaneously carrying communication data, spectrum resources can be utilized more efficiently. Similarly, ref. [71] employs RSMA common streams for sensing, thereby improving communication performance and effectively addressing PLS issues in ISAC systems, particularly in multi-antenna scenarios. However, splitting user messages into common and private streams also increases vulnerability to eavesdropping. In addition, severe path loss and blockage in LoS channels hinder practical deployment.

To alleviate these challenges, RIS is introduced to steer electromagnetic waves toward desired directions. Reference [72] investigates an RSMA-passive RIS-assisted ISAC transmission design, where user message splitting and interference management are jointly optimized while leveraging RIS-induced wave reconfiguration, leading to a significant improvement in EE. In [73], active RIS reflection and amplification modules, AN and RSMA, are jointly exploited to counter unknown eavesdropper locations in ISAC systems, thereby enhancing security. At the same time, STAR-RIS can further improve confidentiality through flexible manipulation of transmitted and reflected signals. Motivated by this, ref. [74] proposes a STAR-RIS-assisted RSMA-ISAC framework. Owing to its flexible message splitting and powerful interference management capabilities, RSMA achieves higher spectral efficiency, user fairness, and robustness to imperfect channel state information

than conventional multiple access schemes [75]. Moreover, ref. [76] introduces sparse code multiple access (SCMA) to further improve reliability. By mapping users to sparse code-words and applying a message passing algorithm (MPA) for multi-user detection, SCMA enables symbol separation with manageable complexity and effectively mitigates IUI.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 7.

Table 7. Summary of optimization objectives and methods for representative MA-assisted ISAC schemes.

Ref.	System Model	Optimization Problem/Main Objective	Method
[65]	NOMA-ISAC	Maximize the weighted sum of communication throughput and effective sensing power	Two-layer penalty-based successive convex approximation (SGA) algorithm
[66]	NOMA-RIS-ISAC	Maximize the sum secrecy rate of all legitimate users subject to BS power budget, minimum user rate, channel-order constraints, RIS phase shifts, and Cramér-Rao lower bound (CRLB) requirements	S-procedure + successive convex approximation (SCA) + semidefinite relaxation (SDR)
[67]	NOMA-RIS-ISAC	Performance evaluation of NOMA-based RIS-assisted ISAC in heterogeneous networks (HetNets)	Homogeneous Poisson point process (PPP)-based stochastic-geometry framework
[68]	NOMA-RIS-ISAC	Joint optimization of DFBS active beamforming, RIS reflection coefficients, and radar receive filter to maximize the sum rate of users	Alternating optimization (AO)
[69]	C-NOMA-RIS-ISAC	Jointly maximize the weighted sum rate and sensing power in a C-NOMA framework	SCA + AO
[70]	RSMA-ISAC	Jointly maximize weighted sum rate (WSR) and minimize radar beam pattern approximation mean-squared error (MSE)	SDMA-based dual-functional radar-communication (DFRC) design framework
[71]	RSMA-ISAC	Maximize EE while ensuring user fairness, sensing performance, and communication security, subject to minimum user rate and secrecy-capacity constraints	Three iterative algorithms based on SCA and penalty-function techniques
[72]	RSMA-RIS-ISAC	Joint optimization of transceiver beamforming, IRS phase shifts, and QoS constraints for integrated communication and sensing	Proximal policy optimization (PPO)-based deep reinforcement learning
[73]	RSMA-RIS-ISAC	Maximize the minimum ergodic partial secrecy rate (EPSR) subject to minimum thresholds on ergodic common secrecy rate, radar sensing performance, and RIS power budget	AO with SCA and MM
[74]	RSMA-STAR-RIS-ISAC	Joint design of BS beamforming vectors and STAR-RIS coefficients to maximize the minimum secrecy rate under minimum beam gain constraints	AO + MM
[76]	SCMA-STAR-RIS-ISAC	Joint beamforming and resource allocation optimization problem	Meta deep reinforcement learning (MDRL) framework

4.2. UAV-Enabled ISAC System

UAVs offer 3D mobility and flexible deployment, providing additional spatial optimization capabilities for ISAC systems. By adjusting their flight trajectories and hovering positions, UAVs can dynamically improve coverage and link quality while enabling real-time target sensing and tracking. These characteristics make UAV-assisted ISAC particularly suitable for applications such as disaster relief, emergency communications, and remote area monitoring.

4.2.1. Single-UAV Cooperative ISAC System

As a key platform bridging airborne, ground, and space segments, a single UAV equipped with a multi-antenna array can simultaneously provide communication services to ground UE and perform target sensing. A typical single-UAV-assisted ISAC system model is illustrated in Figure 10.

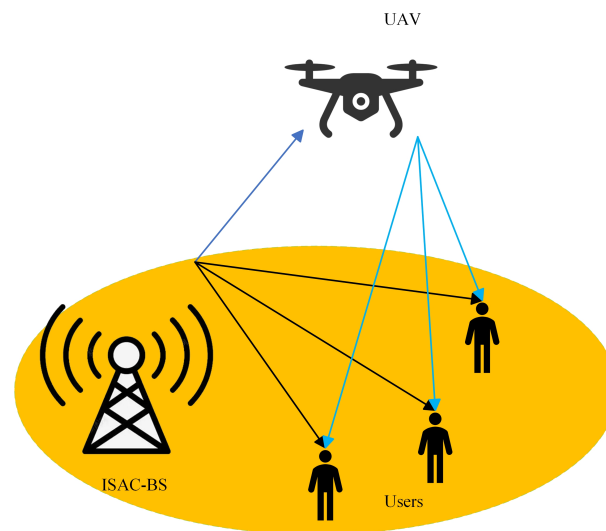


Figure 10. Single-UAV-assisted ISAC system.

4.2.2. Multi-UAV Cooperative ISAC System

While single-UAV systems provide spatial flexibility, their service capacity and coverage are fundamentally limited by the capabilities of a single platform. To support large-scale services and collaborative sensing, multi-UAV systems employ distributed cooperation to overcome these limitations. Compared with single-UAV deployments, cooperative multi-UAV architectures can achieve further improvements in CRB performance due to the geometric diversity offered by multiple airborne radars. However, these gains are accompanied by a substantial increase in system energy consumption and an exponential growth in algorithmic complexity.

As shown in Figure 11, multiple UAVs can collaboratively serve users and sense targets, thereby significantly improving spatial coverage and system robustness. Reference [77] investigates a UAV-based ISAC system in which UAVs act as dual-function aerial access points (APs), exploiting their maneuverability and strong A2G LoS links to realize efficient joint communication and sensing. Reference [78] studies a UAV-assisted collaborative sensing network with ISAC capabilities that can accommodate diverse sensing tasks with different types, accuracy requirements, and sensing intervals. In [79], a game-theoretic optimization framework is proposed for multi-UAV ISAC networks to address the vulnerability of UAV communications to adversarial interference during cooperative missions.

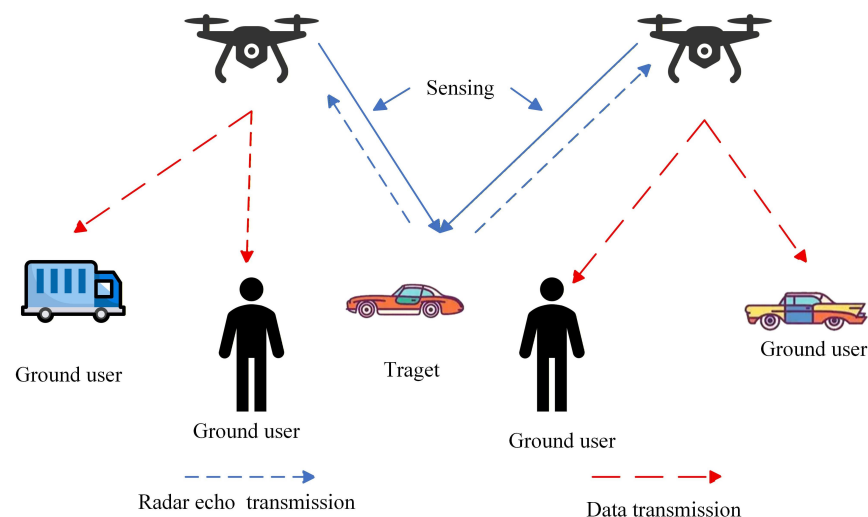


Figure 11. Multi-UAV-assisted ISAC system.

Reference [80] analyzes ISAC channel models for multiple users and targets, studies the interference arising from multi-user communication and echo signals, and employs ADMA to mitigate both multi-user and multi-target interference. In [81], multiple UAVs cooperate with a ground BS to provide joint communication and positioning services for multiple mobile users. Reference [82] proposes a joint beamforming and AN design to jam multiple eavesdropping UAVs, thereby enhancing both communication security and spectral efficiency in dynamic multi-UAV ISAC networks. Finally, ref. [83] introduces a time-assisted frame-structured ISAC framework for multi-UAV networks that integrates search, tracking, and communication functions, while reducing communication overhead and maintaining stable connectivity.

UAV is highly effective for spatial-domain optimization, overcoming the coverage limitations of fixed BS through trajectory planning and power control. Its 3D maneuverability allows UAVs to dynamically adjust service positions, track moving targets, and maintain favorable sensing geometries. These capabilities naturally complement the electromagnetic domain controllability provided by RIS, enabling a synergistic enhancement of communication and sensing performance.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 8.

4.2.3. Application of Multiple Access Techniques in UAV-ISAC Systems

In complex wireless environments with limited LoS paths and severe propagation impairments, ISAC signals are highly susceptible to fading and blockage. The introduction of UAV provides new opportunities to improve link quality and enhance overall system performance.

Reference [84] proposes a multicast-unicast ISAC framework that exploits NOMA to enable dual spectrum sharing between sensing and communication functions as well as between multicast and unicast signals, thereby improving spectral efficiency under bandwidth constraints. Furthermore, ref. [85] develops a NOMA-assisted multi-layer integrated spectrum sharing and collaborative communication (ISCC) system, where the joint optimization of transmit beamforming and computational resource allocation is used to achieve a favorable computation-sensing tradeoff, demonstrating the advantages of NOMA in both capacity enhancement and interference mitigation.

To further improve LoS connectivity, ref. [86] introduces a NOMA-assisted UAV-ISCC architecture in which UAVs act as multifunctional aerial nodes that perform edge

computing for users, transmit integrated sensing and communication beams for target detection, and offload data to fog nodes. By combining this design with NOMA-based decoding, the system can guarantee reliable communication performance while satisfying URLLC constraints. To enhance edge coverage, ref. [87] proposes a C-NOMA-assisted UAV-ISAC model that leverages additional transmit nodes to improve cell-edge user experience, with UAVs serving as aerial BS to support multiple users and significantly increase deployment flexibility. Similarly, ref. [88] exploits the “near user decodes and forwards to far users” mechanism in C-NOMA, together with the rapid deployment and flexible placement of UAVs, to improve system throughput and reliability.

Table 8. Summary of optimization objectives and solution methods for representative UAV-ISAC systems.

Ref.	System Model	Optimization Objective	Main Method
[77]	UAV-ISAC	Jointly design UAV trajectory and transmit information/sensing beamforming to maximize communication throughput while satisfying sensing requirements	AO with SCA and SDR
[78]	UAV-ISAC	Joint optimization of task assignment, UAV trajectory, and power control	Multi-agent proximal policy optimization with action branching and masking (MAPPO-ABAM)
[79]	UAV-ISAC	Mitigate interference, reduce energy consumption, and jointly enhance sensing and communication performance	Electric eel foraging optimization (EEFO)
[80]	UAV-ISAC	Reduce the impact of multi-user and multi-target interference	ADMM
[81]	UAV-ISAC	Joint UAV trajectory design, power control, and BS association to optimize the Cramér-Rao bound (CRB)	BCD with AO and SCA
[82]	UAV-ISAC	Jointly optimize hybrid beamformers, AN, and trajectories of legitimate UAVs to maximize the sum secrecy rate	PPO combined with AO
[83]	UAV-ISAC	Joint UAV beamforming, load management, and heading planning to maximize the total achievable rate in each time slot	Distributed optimization with an improved SCA-iterative rank minimization (IRM) algorithm

For disaster response and other mission-critical scenarios, ref. [89] investigates an RSMA-assisted multi-UAV ISAC system. By splitting user messages into private and common parts with adjustable rates, the system enables customized communication services, while UAV mobility facilitates data collection and delivery to support search-and-rescue operations. In [90], RSMA is used to partition information into common and private components during transmission, providing flexible interference management and effective suppression of interference among multiple users and sensing targets. This design improves reliability, EE, and QoS under varying network conditions. At the same time, RSMA maintains robustness in the presence of imperfect CSI, offering useful guidelines for subsequent joint sensing-communication optimization under CSI uncertainty.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 9.

Table 9. Summary of optimization objectives and methods for NOMA/RSMA-assisted UAV-ISAC systems.

Ref.	System Model	Optimization Problem/Main Objective	Method
[84]	NOMA-ISAC	Unicast rate maximization by optimizing the transmit beamformer, subject to multicast rate constraints and predefined radar beam pattern accuracy	Penalty-based iterative algorithm
[85]	NOMA-ISAC	Joint optimization of BS transmit beamformer and computation-resource allocation between BS and cloud server to maximize computation rate under communication-computation causality and sensing quality constraints	AO based on weighted minimum mean-squared error (WMMSE)
[86]	NOMA-UAV-ISCC	Joint optimization of UAV trajectory, beamforming design, and computation-resource allocation to maximize computation throughput	SAC-TPBD
[87]	NOMA-UAV-ISAC	Maximize average achievable rate subject to QoS constraints of communication users and sensing QoS requirements of moving targets	DDPG
[88]	NOMA-UAV-ISAC	Joint design of BS/UAV beamforming vectors and UAV position to minimize the CRB of target localization under user QoS constraints	DDPG
[89]	CoRSMA-UAV-ISAC	Maximize system weighted sum rate (WSR) while satisfying sensing SNR requirements	K-means clustering, SCA and SDR
[90]	RSMA-UAV-ISAC	Joint beamforming design, UAV trajectory optimization, and BS power allocation to maximize system EE under communication and sensing QoS constraints	Multi-agent twin-delayed DDPG (MATD3)

4.3. RIS-UAV-Enabled ISAC System

The programmable reflection capability of RIS in the electromagnetic domain and the 3D maneuverability of UAVs in the spatial domain form a natural complementarity: RIS enables flexible beamforming, while UAVs provide adaptive positioning. Their integration achieves dual reconfigurability in “spatial positioning $\times$ phase shaping,” supporting dynamic coverage, path reconstruction, and 3D beamforming design.

Figure 12 presents a representative RIS-UAV-assisted ISAC system, which integrates RIS-based electromagnetic environment reconfiguration with UAV-based spatial mobility. In this architecture, the UAV-assisted RIS provides adaptive beam steering, while the UAV’s 3D movement enables dynamic positioning.

This joint design achieves dual reconfigurability in the electromagnetic and spatial domains, allowing dynamic path reconstruction, enhanced coverage, and improved robustness against blockage and interference.

RIS-UAV collaboration enables 3D anti-jamming across the space, time, and frequency domains. Specifically, RIS can flexibly map signals to different delay-Doppler resource blocks via element or sub-surface grouping, while UAVs provide spatial diversity through trajectory adaptation and the deployment of backup RIS modules.

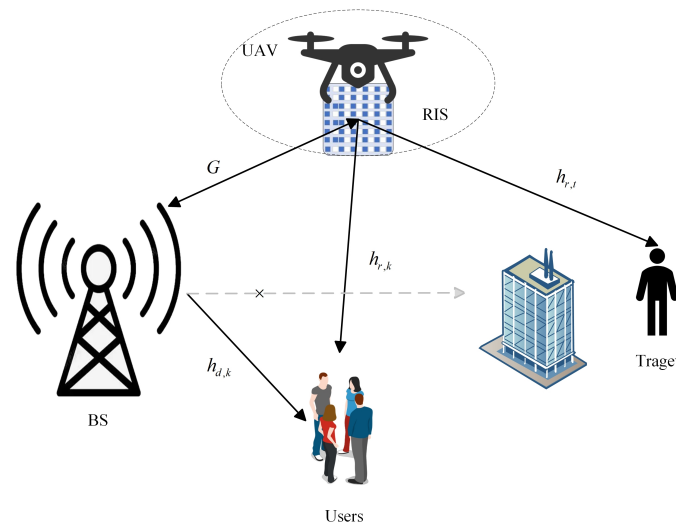


Figure 12. RIS-UAV-assisted ISAC system.

Reference [91] proposes a 3D non-stationary geometric channel model for an AHRIS-assisted ISAC system to accurately capture propagation characteristics. In [92], a reconfigurable holographic surface (RHS)-UAV-based ISAC architecture is introduced, which supports high communication rates under harsh propagation conditions while satisfying minimum sensing SNR requirements. Reference [93] presents a STAR-RIS-UAV near-field ISAC system, where a semi-passive STAR-RIS architecture is used to alleviate severe path loss, thereby significantly improving coverage and sensing performance. In [94], a RIS-autonomous vehicle (AVV)-ISAC system is studied, and a design is proposed to minimize the weighted sum of multi-user interference (MUI) and sensing beam pattern mismatch (BPM) under peak-to-average power ratio (PAPR) constraints.

Reference [95] proposes a multifunctional RIS (MF-RIS)-enhanced UAV-ISAC system, in which the MF-RIS simultaneously supports reflection, refraction, and amplification to strengthen omnidirectional signals, mitigate double fading via amplification, and improve overall system effectiveness. In [96], a RIS-AVV-ISAC framework is developed to jointly satisfy communication and sensing requirements in complex environments, enabling dynamic balancing of resource allocation, AVV trajectory planning, and interference management. Reference [97] focuses on reducing learning complexity and mitigating gradient interference in single-policy networks, thereby accelerating convergence and improving optimization efficiency.

In [98], RIS is mounted on UAVs as a flexible relay to improve EE in the presence of malicious interference. Reference [99] proposes a RIS-UAV-ISAC system that enables secure multi-user communication while simultaneously detecting potential malicious radar targets. In [100], a semi-supervised channel-mapping framework for UAV navigation is introduced, where RIS is used to enhance channel diversity and signal coverage. Reference [101] considers a scenario in which a RIS-UAV-ISAC system simultaneously detects untrusted targets in the surrounding environment and communicates with ground IoT devices, enabling covert communication in the presence of an eavesdropper (Eve). In [102], RIS combining active and passive elements is employed to enhance A2G communications for multiple users while sensing multiple low-mobility targets. Finally, ref. [103] studies a fairness-oriented design for joint communication and sensing, aiming to maximize the minimum achievable rate among all users.

The core optimization objectives and corresponding solution methods of this system are summarized in Table 10.

Table 10. Summary of optimization objectives and methods for representative RIS/HRIS-UAV-ISAC systems.

Ref.	System Model	Optimization/Main Objective	Method
[91]	AHRIS-ISAC	Develop a novel 3D geometric-based stochastic model (GBSM) that captures non-stationarity caused by platform jitter and the correlation between sensing and communication channels	Geometric-based stochastic channel modeling and analysis
[92]	RHS-UAV-ISAC	Joint design of BS digital beamforming, RHS holographic beamforming, and RIS passive beamforming to enhance ISAC performance	AO
[93]	STAR-RIS-UAV near-field ISAC	Joint optimization of transmit beamforming vectors, reflection/transmission matrices, and UAV position to maximize the weighted sum rate	AO
[94]	RIS-AVV-ISAC	Joint waveform design to minimize the weighted sum of MUI and beam-pattern mismatch (BPM) under power, PAPR, ideal beam-direction approximation, and constant-modulus (CM) constraints	Multivariate cyclic iterative ADMM (MCI-ADMM)
[95]	MF-RIS-UAV-ISAC	Joint optimization of beamforming, UAV trajectory, and MF-RIS coefficients to maximize radar signal-to-interference-plus-noise ratio (SINR)	AO
[96]	RIS-AVV-ISAC	Joint optimization of autonomous aerial vehicle (AAV) trajectory, beamforming matrices, and RIS phase shifts to improve joint sensing and communication performance	DDPG, TD3 and PPO
[97]	RIS-UAV-ISAC	Joint optimization of transmit/receive beamforming matrices and RIS phase shifts to maximize sensing SNR	Mixture-of-experts (MoE) PPO
[98]	RIS-UAV-ISAC	Joint optimization of BS transmit power, RIS reflection coefficients, active RIS ratio, and UE channel selection under communication rate and information leakage constraints	Stackelberg game (SG)-guided soft double deep deterministic policy gradient (SD3)
[99]	RIS-UAV-ISAC	Minimize the CRB subject to UAV flight-region constraints, QoS, secrecy, transmit power budget, and RIS reflection constraints	AO
[100]	RIS-UAV-ISAC	Provide reliable CSI-driven UAV positioning via channel-feature mapping	Semi-supervised Siamese neural network with UMAP-based manifold learning
[101]	RIS-UAV-ISAC	Joint optimization of UAV trajectory, RIS passive beamforming, transmit beamforming, and receive beamforming to maximize average secrecy rate	BCD
[102]	HRIS-UAV-ISAC	Joint design of transmit and phase-shift beamforming and UAV trajectory to enhance joint communication and sensing performance	Transfer-learning-based DDPG
[103]	HRIS-UAV-ISAC	Joint optimization of UAV position/trajectory, transmit beamformers, and RIS coefficients to maximize the minimum user rate (fairness-oriented design)	BCD

4.4. Performance Evaluation and Analysis

Based on the evaluation framework proposed in Section 2, representative studies [25,99,104–106] are analyzed and compared.

As shown in Table 11, passive RIS can achieve high data rates and sensing accuracy with low power consumption and moderate complexity. Active RIS improves sensing performance through signal amplification but exhibits lower EE. STAR-RIS provides a balanced tradeoff between communication and sensing while enabling full-space coverage. UAV-RIS leverages platform mobility to enhance sensing accuracy, but this comes at the cost of high energy consumption and significantly increased complexity. Combining active RIS with RSMA markedly improves communication rate and interference management capability, although it suffers from limited sensing accuracy and reduced EE.

Table 11. Comparison of representative RIS/STAR-RIS/active RIS-assisted ISAC schemes under a four-dimensional evaluation framework.

Ref.	Model	Comm. Rate	Sensing Accuracy	EE	Complexity
[25]	Passive RIS	High	High	High	Medium
[104]	Active RIS	Medium	Extremely High	Low	High
[105]	STAR-RIS	High	High	Medium	High
[99]	UAV-RIS	Medium	Extremely High	Low	Very High
[106]	Active RIS + RSMA	Very High	Medium	Low	High

Overall, intelligent optimization methods provide diverse design options for RIS-UAV-ISAC systems. However, achieving a balanced tradeoff among communication rate, sensing accuracy, EE, and algorithmic complexity remains a central challenge for future research.

4.5. Chapter Summary

This section has systematically reviewed RIS-assisted and UAV-enabled ISAC architectures from a cooperative perspective. On the one hand, different types of RIS—including passive RIS, active RIS, hybrid RIS, and STAR-RIS—provide flexible electromagnetic environment control by enabling programmable reflection, transmission, and amplification, thereby enhancing communication coverage and sensing accuracy under diverse deployment scenarios. On the other hand, UAVs offer 3D mobility and adaptive positioning capabilities, which significantly improve line-of-sight conditions, spatial diversity, and sensing geometry in dynamic environments.

By integrating RIS and UAV technologies, RIS-UAV-ISAC systems achieve dual re-configurability in both the electromagnetic and spatial domains, enabling dynamic path reconstruction, adaptive beamforming, and enhanced robustness against blockage and interference. Furthermore, the joint consideration of RIS-UAV architectures with advanced multiple access techniques, such as NOMA and RSMA, allows more efficient spectrum utilization and flexible interference management in multi-user and multi-target scenarios.

Overall, the reviewed studies indicate that RIS-assisted and UAV-enabled cooperative ISAC architectures offer a promising solution for balancing communication performance, sensing accuracy, energy efficiency, and system complexity. These architectures lay a solid foundation for future ISAC system designs that require high adaptability, scalability, and robustness under practical deployment constraints.

5. Future Directions and Challenges

5.1. Intelligent Evaluation and Dynamic Optimization Framework

CRB frameworks are difficult to apply in non-stationary, rapidly time-varying channels, and fixed performance metrics cannot effectively capture the fast-fading characteristics of millimeter-wave links. To overcome these limitations, future research should develop an evaluation framework that integrates artificial intelligence with information theory. In such a framework, deep neural networks can be used to accelerate real-time mutual information computation and design dynamic performance indicators, such as ergodic partial CRB.

By leveraging a multi-domain co-simulation platform, the robustness of this framework can be validated in highly interfered industrial environments, and a quantitative mapping between sensing accuracy and spectral efficiency can be established. At the same time, a hybrid multiple access protocol is needed to mitigate spectral efficiency degradation caused by static access schemes. This protocol should tightly couple time-division and frequency-division mechanisms with AI-driven resource allocation, enabling real-time adaptation of NOMA power domains and RSMA coding streams according to the inferred channel state.

Furthermore, exploiting distributed computing capabilities at edge nodes enables joint optimization of spectrum and EE under stringent latency constraints, such as in vehicular networks. This approach can increase the number of concurrently served IoT devices and provide dynamically configurable cross-layer optimization interfaces for future 6G networks.

5.2. Cooperative Control and Resilient Network Architecture

In RIS-UAV cooperative ISAC systems, even nanosecond-level clock synchronization errors among multiple nodes can lead to data fusion distortion and significantly degrade sensing accuracy. Future systems, therefore, require distributed space-time synchronization protocols. By jointly optimizing RIS phase-delay compensation and UAV swarm collaborative navigation, temporal jitter along multi-hop transmission paths can be substantially reduced.

To address UAV positioning drift caused by environmental factors such as strong wind, machine learning can be used to optimize the 3D elastic network topology. Combined with software-defined networking (SDN), this enables dynamic protocol reconfiguration by integrating terrestrial BS with low-Earth-orbit satellite backhaul paths, thereby forming a 3D elastic network architecture. In disaster and emergency scenarios, this architecture can support millisecond-level self-healing link reconfiguration. These techniques are expected to improve positioning accuracy to the centimeter level, ensure continuous communication and sensing services during urban search-and-rescue operations, and maintain system resilience under Tbps-level data rates.

5.3. Secure Federated Learning and Privacy Protection

Federated learning and other AI-based optimization methods can significantly enhance the computational efficiency of distributed ISAC systems, but they also introduce risks of privacy leakage and cross-domain generalization bottlenecks. Future work should, therefore, focus on constructing lightweight and trustworthy federated learning frameworks that tightly integrate differential privacy with homomorphic encryption. Applying local differential privacy perturbations to gradient updates and embedding traceable digital fingerprints can lower the success rate of data reconstruction attacks.

In addition, meta-learning can be exploited to improve cross-scenario adaptability, enabling multi-institution collaborative modeling in areas such as intelligent healthcare without sharing raw data. Strengthening secure multi-party computation is also essential, including the use of encrypted communication protocols and identity authentication mechanisms to protect the security of parameter exchange. Finally, designing robust model architectures that are resilient to malicious or noisy data can reduce misclassification rates in industrial automation systems and improve fraud detection accuracy in financial risk control.

6. Conclusions and Future Work

This paper systematically reviews ISAC architectures assisted by RIS and cooperative UAV and introduces the application of advanced multiple access techniques in these systems. Subsequently, a four-dimensional evaluation framework is employed to comparatively assess representative studies in terms of communication performance, sensing accuracy, resource efficiency, and system complexity. Finally, based on the reviewed systems, the associated challenges and potential future research directions are then discussed.

Author Contributions: Conceptualization: Z.L.; Methodology: Y.Z.; Investigation: W.W. and W.T.; Writing—original draft preparation: Y.Z.; Writing—review and editing: Z.L. and Y.Z.; Supervision: Z.L.; Project administration: Z.L.; Funding acquisition: Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Sichuan Province Science and Technology Support Program under Grant 2026NSFSC0394, in part by the National Natural Science Foundation of China under Grant 61801319, in part by the Opening Project of the Intelligent Perception and Control Key Laboratory of Sichuan Province under Grant 2021RZJ01, in part by the Scientific Research and Innovation Team Program of Sichuan University of Science and Engineering under Grant SUSE652A011, and in part by the Postgraduate Innovation Fund Project of Sichuan University of Science and Engineering under Grant Y2025078.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

Abbreviations

Abbreviation	Full Name
A2G	Air-to-Ground
AAV	Autonomous Aerial Vehicle
ADMM	Alternating Direction Method of Multipliers
AI	Artificial Intelligence
AN	Artificial Noise
AO	Alternating Optimization
APs	Access Points
ARIS	Active Reconfigurable Intelligent Surface
AST	Average System Throughput
AVV	Autonomous Vehicle
BCD	Block Coordinate Descent
BPM	Beam pattern Mismatch
BS	Base Station
CCCP	Concave-Convex Procedure
C-NOMA	Cooperative Non-Orthogonal Multiple Access
CRB	Cramér-Rao Bound
CRLB	Cramér-Rao Lower Bound
CSMM	Constrained Stochastic Majorization-Minimization
CSI	Channel State Information
DFRC	Dual-Functional Radar and Communication
DL	Deep Learning
DoA	Direction of Arrival
DoF	Degrees of Freedom
DDPG	Deep Deterministic Policy Gradient
DRL	Deep Reinforcement Learning
EE	Energy Efficiency

EEFO	Electric Eel Foraging Optimization
EPSR	Ergodic Partial Secrecy Rate
ES	Energy Splitting
FIM	Fisher Information Matrix
FL	Federated Learning
FP	Fractional Programming
FPI	Fixed-Point Iteration
GFP	Generalized Fractional Programming
HetNet	Heterogeneous Network
HP	Hybrid Precoding
HRIS	Hybrid Reconfigurable Intelligent Surface
IMT	International Mobile Telecommunications
ITU	International Telecommunication Union
IoT	Internet of Things
IUI	Inter-User Interference
ISAC	Integrated Sensing and Communication
ISCC	Integrated Spectrum Sharing and Collaborative Communication
LAS-IoT	Low-Altitude Smart Internet of Things
LoS	Line-of-Sight
MA	Multiple Access
MAPPO-ABAM	Multi-Agent Proximal Policy Optimization with Action Branching and Masking
MATD3	Multi-Agent Twin-Delayed Deep Deterministic Policy Gradient
MDRL	Meta Deep Reinforcement Learning
MIMO	Multiple-Input Multiple-Output
MM	Majorization-Minimization
MOMP	Multi-Dimensional Orthogonal Matching Pursuit
MPA	Message Passing Algorithm
MSE	Mean-Squared Error
MUI	Multi-User Interference
NOMA	Non-Orthogonal Multiple Access
PC	Passive Sensing
PAPR	Peak-to-Average Power Ratio
PDD	Penalty Dual Decomposition
PL	Path Loss
PLS	Physical-Layer Security
PPO	Proximal Policy Optimization
PRIS	Passive Reconfigurable Intelligent Surface
QoS	Quality of Service
RA	Reflection Amplifier
RIS	Reconfigurable Intelligent Surface
R-SACE	RIS-Assisted Sensing-Aided Communication Enhancement
RSMA	Rate-Splitting Multiple Access
RHS	Reconfigurable Holographic Surface
SAGIN	Space-Air-Ground Integrated Network
SCA	Successive Convex Approximation
SC-ARIS	Subcarrier-Based Active Reconfigurable Intelligent Surface
SCMA	Sparse Code Multiple Access
SCNR	Signal-to-Clutter-plus-Noise Ratio
SDR	Semidefinite Relaxation
SDP	Semidefinite Programming
SER	Symbol Error Rate
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-plus-Noise Ratio

SLP	Symbol-Level Precoding
SNR	Signal-to-Noise Ratio
SR	Secrecy Rate
STAR-RIS	Simultaneous Transmission and Reflection Reconfigurable Intelligent Surface
STAP	Space-Time Adaptive Processing
TS	Time Switching
UAV	Unmanned Aerial Vehicle
UE	User Equipment
URLLC	Ultra-Reliable Low-Latency Communication
V2X	Vehicle-to-Everything
VR	Virtual Reality
VLoS	Virtual Line-of-Sight
WMMSE	Weighted Minimum Mean-Squared Error
WSR	Weighted Sum Rate
6G	Sixth-Generation
2D	Two-Dimensional
3D	Three-Dimensional
3GPP	Third Generation Partnership Project

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