Air-Ground Collaborative ISAC for LAE: UAV Swarms as Virtual Aerial Arrays for 3D Observability and Seamless Mobility

Nanchi Su, Hongjia Huang, Xiaoye Jing, Qinyu Zhang, and Tse-Tin Chan

Abstract

The emerging low-altitude economy (LAE) is driving growing demand for three-dimensional (3D) situational awareness and ubiquitous connectivity in dynamic low-altitude operations. However, conventional terrestrial cellular networks, originally designed for ground coverage, exhibit limited vertical beam directivity and angular resolution in aerial environments, thereby hindering the reliable sensing of low-altitude objects under occlusions and weak backscatter conditions. This article advocates an air-ground collaborative integrated sensing and communication (ISAC) architecture, where UAV swarms serve as virtual aerial arrays to complement ground infrastructure and close the 3D observability gap. By leveraging sensing for mobility and network coordination, including predictive beam alignment and handover pre-staging, the framework improves link reliability and continuity.

Introduction

The rapid expansion of the low-altitude economy (LAE) relies on the large-scale deployment of uncrewed aerial vehicles (UAVs), airborne delivery systems, and autonomous air taxis operating in shared three-dimensional (3D) airspace across urban and rural regions [1]. The resulting surge in aerial traffic significantly increases the complexity of airspace management and network operations, requiring regulatory authorities and service providers to ensure tighter situational awareness and more reliable connectivity.

However, terrestrial base stations (BSs), originally optimized for ground coverage, observe low-altitude UAVs from grazing elevation angles, which fundamentally limits vertical resolution and creates blind zones even under dense deployments. These geometric constraints are compounded in practice by weak and fluctuating backscatter from small aerial targets and by urban blockage that can simultaneously eliminate multiple ground viewpoints [2]. Meanwhile, high UAV mobility leads to frequent cell crossings and rapid beam misalignment, pushing measurement, beam search, and handover signaling toward bursty, near-trigger operation and increasing interruption risk under directional links.

Embedding integrated sensing and communication (ISAC) into cellular networks has emerged as a promising direction to enhance awareness and robustness [3]. However, closing the 3D observability gap requires extending sensing geometry beyond the ground plane. To this end, we advocate a collaborative air-ground ISAC architecture in which UAV swarms act as reconfigurable sensing and communication (S&C) nodes that complement terrestrial BS anchoring. We develop a three-component framework consisting of terrestrial BSs for wide-area coverage, backhaul, and control anchoring; UAV swarms operating as virtual aerial arrays (VAAs) that provide elevation-diverse multi-view observations; and an edge-cloud controller that fuses sensing information and orchestrates mobility actions. The proposed framework leverages sensing to enable network-side mobility intelligence rather than replacing dedicated uncrewed aircraft system (UAS) traffic management (UTM) or airspace surveillance infrastructures [4]. We also discuss sensing-communication trade-offs, architectural resilience, and key engineering challenges toward 6G integration. The main contributions of this article are summarized as follows.

The main novelty of this article is the use of UAV swarms as reconfigurable VAAs, rather than only as mobile terminals or relays, to provide altitude-diverse viewpoints for improving 3D observability. The resulting 3D state awareness can support beam pre-alignment and handover pre-staging, thereby reducing beam-search overhead and mitigating control-plane signaling bursts under high mobility.

- We propose a collaborative air-ground ISAC architecture that leverages UAV swarm

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Digital Object Identifier: 10.1109/MCOM.001.2600190

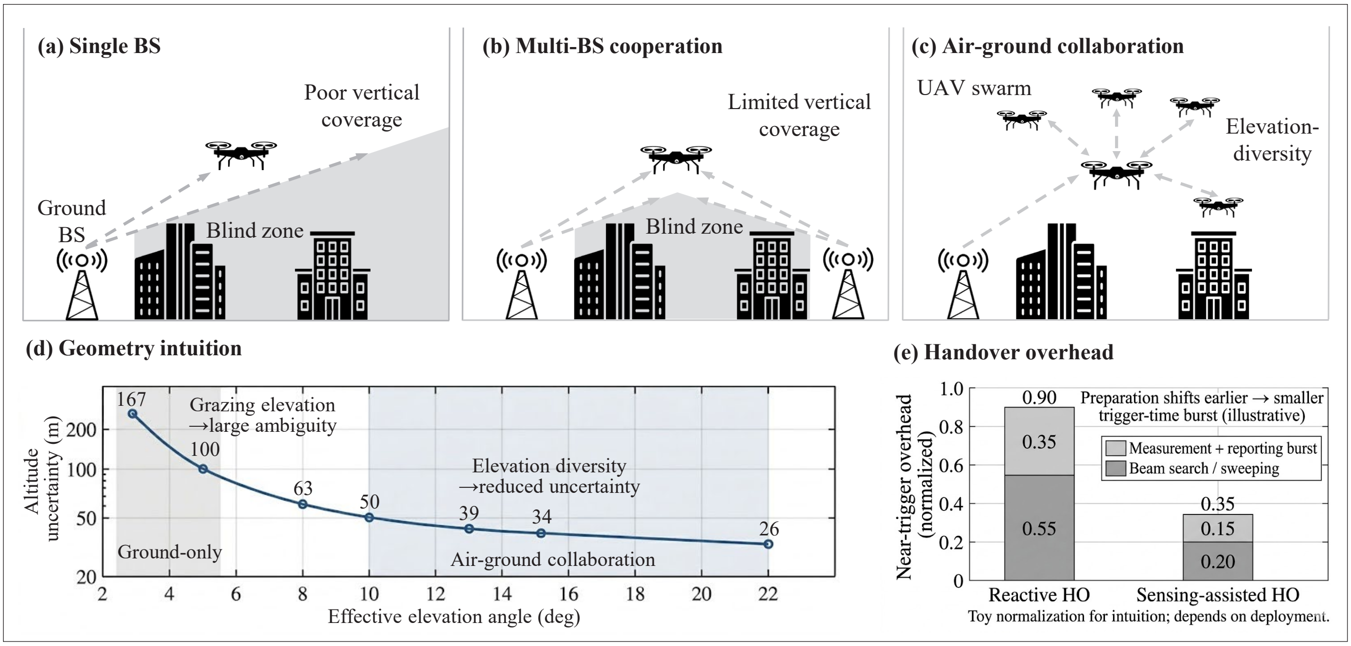

FIGURE 1. Schematic comparison of observability under different deployment strategies. A single terrestrial BS provides limited vertical coverage. Multi-site terrestrial cooperation partially mitigates these limitations but remains constrained by ground-based geometry. Air-ground collaborative ISAC with a UAV swarm introduces elevation-diverse, multi-viewpoint observations that resolve 3D position ambiguities.

reconfigurability to complement terrestrial BS anchoring, enabling integrated 3D sensing and connectivity for low-altitude networks.

- We introduce the concept of VAAs and characterize their cooperative design space, including key trade-offs between coherent/non-coherent processing and active/opportunistic sensing modes, as well as the implications of near-field propagation conditions.
- We develop a closed-loop sensing-assisted mobility framework that transforms handover from a reactive procedure into a predictive, multi-stage workflow, substantially reducing beam-search overhead and control-plane signaling bursts.
- We analyze the trade-offs between S&C and identify open challenges in synchronization, latency partitioning, occlusion robustness, and standardization, providing practical design insights for 6G systems.

The remainder of this article is organized as follows. We quantify the 3D observability gap of terrestrial sensing and motivate the need for air-ground collaboration. We introduce the VAA-enabled sensing model and key design dimensions. We present the closed-loop sensing-assisted mobility framework and representative use cases. We discuss major sensing-communication trade-offs, and we highlight open challenges and research directions.

The 3D Observability Gap: Why Air-Ground Collaborative ISAC Is Needed

In conventional networks, techniques such as coordinated multipoint (CoMP) transmission in LTE [5], cell-free massive MIMO [6], and advanced mobility management exploit spatial diversity across terrestrial sites to enhance throughput, reliability, and coverage. These approaches can also improve connectivity in low-altitude scenarios by increasing path diversity and mitigating shadowing. However, they do not alter the ground-constrained geometry that fundamentally limits 3D observability.

Specifically, terrestrial BSs remain confined to fixed ground deployments with limited antenna heights, leading to elevation angles concentrated near grazing directions for low-altitude targets. For example, a UAV flying at 50 meters is still observed at shallow elevation angles by a 30-meter BS, and even raising the BS height to 90 meters provides only limited improvement, which remains insufficient for reliable 3D localization. This problem is further intensified by urban occlusion, where building blockage can simultaneously interrupt line-of-sight paths from multiple terrestrial sites and reduce the benefit of coordination. Without elevation diversity introduced by nodes operating at substantially different altitudes, ground-based cooperation alone cannot recover the missing geometric information. As illustrated in Fig. 1, multi-site terrestrial coordination provides useful spatial diversity but remains constrained by ground-based geometry, whereas air-ground collaborative ISAC with UAV swarms can introduce elevation-diverse viewpoints that help reduce 3D positional uncertainty.

The above observations motivate the integration of air-ground collaboration into low-altitude network architectures. In the proposed framework, UAVs are no longer treated merely as managed terminals but operate as active S&C nodes within the ISAC network [1]. The architecture comprises three interacting components: terrestrial BSs for backhaul and control anchoring, UAV swarms for elevation-diverse sensing and cooperative transmission, and an edge or cloud controller for measurement fusion and resource coordination. By leveraging multi-view observations and trajectory prediction, the network transforms mobility management from reactive recovery into proactive preparation, mitigating beam-search overhead and control-plane signaling bursts under high mobility.

Low-altitude networks inherently require three-dimensional modeling, as observability and parameter identifiability depend critically on elevation diversity.

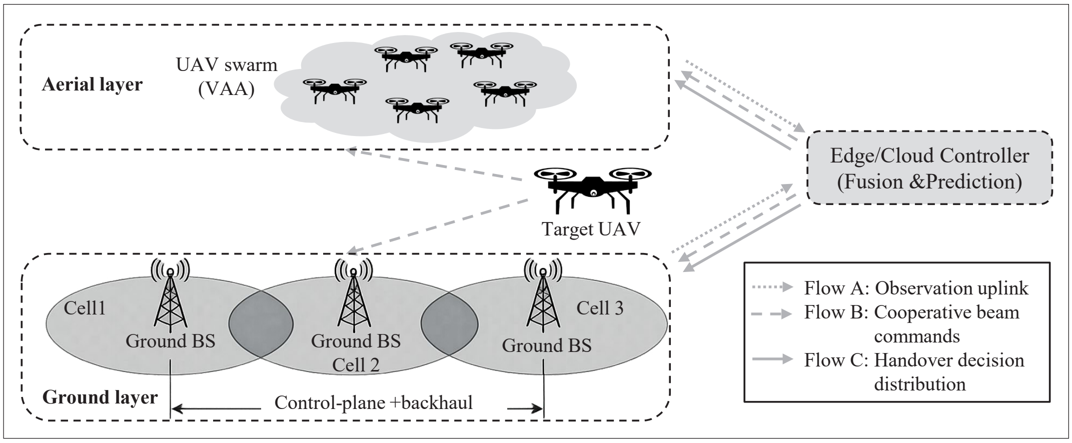

FIGURE 2. Air-ground collaborative ISAC functional architecture and information flows: A) sensing feature uplink from ground and aerial nodes to the edge controller; B) beam and pilot assistance commands distributed to candidate BSs; and C) handover context distribution via the edge controller enabling proactive prepare-and-switch operations.

System and Modeling Essentials: 3D Observability and VAAs

Virtual Aerial Arrays: Definition and Taxonomy

A UAV swarm forms a virtual aerial array (VAA) when its distributed nodes provide multi-perspective observations or participate in coordinated transmission and reception whose signals are jointly fused to achieve S&C performance beyond that of any single platform. Fusion may be coherent or non-coherent, depending on synchronization capability and target performance. The design space is characterized along two dimensions: inter-node cooperation and illumination strategy. Coherent cooperation requires strict phase and time alignment to enable distributed beamforming or MIMO transmission, offering substantial spatial gain at the cost of stringent synchronization. Non-coherent cooperation instead fuses independently estimated AoA, ToA, and Doppler parameters from multiple viewpoints, relaxing synchronization requirements while enhancing geometric observability. Regarding illumination, active sensing transmits dedicated probing or pilot signals using UAVs alone or jointly with ground BSs, whereas opportunistic sensing reuses communication pilots and extracts sensing information from them. In practical low-altitude deployments, non-coherent fusion typically underpins the observation layer, active illumination is selectively enabled by ground and aerial nodes, and coherent operation is reserved for high-precision scenarios with sufficient synchronization support.

Coherent fusion offers high spatial gain but requires strict synchronization and is sensitive to Doppler shifts. Non-coherent fusion combines independently estimated AoA, ToA, and Doppler measurements, providing robust geometric observability with relaxed timing constraints. Active sensing transmits dedicated probing signals to improve measurement fidelity, while opportunistic sensing extracts information from communication pilots with minimal overhead. Designers select the mode based on deployment conditions, mission-critical requirements, and UAV coordination capabilities.

3D State and Observation Modeling

The proposed framework targets mobility management rather than full airspace surveillance. The sensing subsystem therefore tracks a compact state vector comprising 3D position, velocity, and flight intent encoded as planned waypoints. Observations across the multi-static air-ground network include AoA, ToA, Doppler, and backscatter amplitude measurements from ground and aerial nodes. These multi-view measurements are fused into consistent 3D state estimates and short-horizon trajectory predictions, which support beam pre-alignment and handover pre-staging. For mobility-centric operation, sub-second update rates and meter-level positioning accuracy are generally sufficient for reliable handover prediction. By contrast, comprehensive airspace traffic management demands finer spatial resolution and stricter latency guarantees.

Low-altitude networks inherently require three-dimensional modeling, as observability and parameter identifiability depend critically on elevation diversity. Conventional 2D AoA formulations that parameterize targets by azimuth and elevation relative to a single ground BS introduce strong coupling among distance, elevation, and horizontal position. As a result, measurement noise and multipath can significantly distort the inferred 3D trajectory. These ambiguities can be mitigated only through multi-view observations obtained from spatially separated ground sites or airborne nodes operating at distinct altitudes.

For illustration, consider a UAV at 50m observed by a terrestrial node at 30m with a horizontal range of 500m, yielding an elevation angle of roughly 2°, which provides limited vertical discrimination. Adding an aerial node at 150m introduces an additional sightline separated by about 11° in elevation, producing an included angle of approximately 13°. Even with 1° angular uncertainty per node, simple triangulation error propagation bounds the altitude estimate within roughly 40m, whereas the single-view case leaves altitude effectively unbounded. Further increasing altitude diversity or incorporating additional viewpoints tightens the estimation bound.

Beyond elevation geometry, propagation effects further affect 3D parameter recovery. In low-altitude scenarios, target distance may be comparable to the array aperture [7], rendering near-field effects non-negligible. Under such conditions, far-field beam assumptions introduce systematic bias in angle and range estimation. Accurate recovery therefore requires spherical wave modeling and distance-dependent phase characterization, particularly when fusing ground and aerial observations at different altitudes. These considerations motivate a unified 3D state representation across platforms. Although terrestrial BSs are fixed and UAV swarms are mobile, both observe the same underlying 3D position and velocity. Ground arrays provide measurements from known locations, while UAV-mounted arrays offer reconfigurable viewpoints that reshape sensing geometry. A fusion module consolidates these measurements into consistent state estimates, exploiting multi-altitude diversity to enhance observability.

This modeling framework underpins the mechanisms developed in the following section. Multi-view geometry alleviates elevation constraints in cooperative beamforming, trajectory prediction enables proactive beam alignment and handover preparation, and coordinated control balances S&C objectives.

Key Enablers: Cooperative Beamforming, Sensing-Assisted Mobility, and Resource Orchestration

Air-ground collaborative ISAC is enabled by three tightly coupled components: cooperative beamforming, sensing-assisted mobility, and resource orchestration. Cooperative beamforming shapes spatial directivity and mitigates blockage, sensing provides timely state awareness for mobility decisions, and orchestration coordinates S&C to avoid contention. Their interaction determines the effectiveness of the architecture in dynamic low-altitude environments.

Cooperative Beamforming and Multi-Static Sensing

Cooperative beamforming leverages distributed antenna elements across ground and aerial platforms to concentrate energy and compensate for obstructed links. When a terrestrial BS-UAV link is blocked, neighboring BSs or aerial relays can illuminate the same airspace from alternative angles, and performance gains arise from coherent or non-coherent signal combination across viewpoints. In the sensing domain, cooperative illumination improves the detectability of weak backscatter from small airborne targets. Multiple UAVs observing from spatially separated locations form a multi-static radar geometry [8], which offers greater spatial diversity and robustness to specular reflections than monostatic configurations. Weak returns at one node may be stronger at another, and fusing these complementary measurements enhances parameter estimation accuracy. Note that the aerial component is particularly valuable in urban deployments, where terrestrial BS density is limited by infrastructure constraints. Mobile UAV relays and sensing nodes can be repositioned as needed without permanent installations, complementing fixed ground arrays and improving resilience to congestion and occlusion.

In practice, effective cooperative beamforming requires synchronized pilot transmission, accurate geometry calibration, and distributed receive buffering, typically within sensing windows of tens of milliseconds. Maintaining phase and time coherence across mobile aerial nodes remains a key challenge under high mobility and rapidly varying channels.

Sensing-Assisted Handover and Trajectory-Aware Mobility Management

In conventional cellular systems, handover is triggered only after link quality degrades, introducing latency in the measurement-report-beam-search cycle and increasing disconnection risk for highly mobile UAVs. Sensing-assisted handover overcomes this limitation by continuously tracking airborne targets, estimating their 3D state, and predicting short-horizon trajectories [9]. Based on these predictions, the network can pre-select candidate cells, pre-align beams, and configure pilots and control-plane resources before severe link degradation occurs. When the trigger is reached, execution may be reduced to confirmation and switching along a prepared path rather than initiating a new discovery process. This shift from reactive recovery to proactive preparation moves control operations such as measurement requests and beam searches to earlier, less congested stages, reducing delay and signaling overhead. For high-speed UAVs, predictive preparation also enables brief multi-BS connectivity during transition, lowering the risk of interruption.

The fusion controller aggregates multi-static observations, performs motion prediction [10], and distributes trajectory forecasts to candidate BSs. Based on these predictions, pre-staging activates prioritized beam sets and allocates dual-connectivity resources ahead of the trigger event, allowing the UE to switch without a new beam sweep. After execution, residual timing offsets and selected beam indices are fed back to refine prediction and alignment parameters, forming a closed-loop adaptation mechanism. Table 1 contrasts reactive and sensing-assisted procedures, highlighting how sensing shifts computationally intensive operations to earlier stages.

From an implementation perspective, sensing-assisted handover depends on timely multi-static observations, accurate trajectory prediction, and low-latency backhaul to candidate cells. Beam pre-alignment operates on millisecond scales, while pilot pre-staging occurs within sub-second intervals. A key challenge is minimizing backhaul delay when disseminating prediction results to ensure that proactive preparation remains effective under mobility.

The framework is presented as a conceptual approach, and detailed evaluation of signaling overhead, handover latency, and the impact of prediction errors is deferred to future studies.

Dynamic Resource Orchestration

Dynamic resource orchestration balances spectrum, power, and processing allocations across S&C tasks while adapting to airspace activity and network conditions. Edge processors handle time-critical operations such as feature extraction, track updates, beam-prior generation, and handover preparation, whereas cloud resources support longer-horizon trajectory modeling and cross-area coordination. Compute allocation adjusts to mobility risk and prediction uncertainty, prioritizing urgent tasks at the edge and deferring or offloading less critical ones to conserve energy. Cooperative set selection reduces backhaul load and energy consumption by choosing the minimal set of ground and aerial nodes that meets S&C requirements,

Air-ground collaborative ISAC is enabled by three tightly coupled components: cooperative beamforming, sensing-assisted mobility, and resource orchestration.

HO function block	NR baseline	Assisted by sensing (predict first, then confirm)	ISAC-enabled information
Trigger and decision timing	Often triggered after link or beam degradation; near-trigger measurements drive decisions, compressing control signaling time.	Triggered by a predicted boundary crossing or an anticipated quality drop; near trigger focuses on confirmation and switching.	3D state with uncertainty; occlusion likelihood; predicted quality trend.
Candidate cell/TRP selection	Neighbor lists with scanning may yield a large candidate set in dense deployments; overhead increases and selection is delayed.	Trajectory- and geometry-aware pruning yields a small, ranked candidate set; the shortlist can be distributed early.	Geometry-aware ranking (elevation and view-angle diversity), occlusion-aware pruning, confidence tags.
Measurement and reporting placement	Reports concentrate around the trigger (often when the serving link is weak), creating control-plane bursts and stale information.	Reporting is amortized over a prediction window; shift from frequent raw reports to feature- or track-level fusion with fallback.	Track-level updates (state and confidence); beam priors; fallback guard when confidence drops.
Beam management	Beam re-discovery and sweeping often happen close to (or after) the trigger; interruption risk increases in directional bands (e.g., FR2).	Candidate beams are pre-aligned before the trigger; trigger-time reduces to fast confirmation/selection; keep BFR as a safety net.	AoA- or trajectory-driven beam priors; blockage prediction to reduce sweeping and RA retries.
Conditional HO and early configuration	Target parameters and conditions are configured shortly before execution; fast dynamics can outpace reconfiguration.	Use conditional configurations to pre-store switching rules; near trigger the UE follows pre-provisioned conditions.	Predicted condition-satisfaction time with confidence to tune conservative thresholds and reduce false triggers.
Preparation (context and resources)	Context transfer and resource preparation start after the decision and are time-compressed; resources may be requested under urgency.	Preparation begins earlier: distribute the estimated arrival time, reserve short pilot/beam windows, and pre-warm target-side context.	Lightweight reservation of "when" and "where"; uncertainty drives reservation breadth (single- vs. multi-target).
Synchronization and random access friction	Timing acquisition and random access (RA) occur during execution; failures and retries add latency and disruption.	Pre-staged synchronization (e.g., pilots) with timing and beam priors reduces RA friction; execution approaches a fast switch when reliable.	Timing and beam priors with confidence-aware gating (fallback to conventional RA if priors are unreliable).
Execution and continuity	RRC reconfiguration and synchronization may incur brief interruption; continuity depends on both link and beam success.	If multi-connectivity is available, enable overlap (make-before-break); otherwise reduce interruption via pre-alignment and preparation.	Earlier overlap planning; readiness and uncertainty determine overlap versus hard switch.
Path switch and closed-loop recovery	Path switch and buffering occur after execution; failures may escalate to RLF and re-establishment.	Feedback refines prediction and beam priors; keep secondary candidates warm for fast fallback if confidence collapses.	Use outcomes and residual errors (timing and beam) for online calibration; cross-view consistency can flag anomalies (resilience).

Notes and standard hooks: NR mobility and RRC procedures (e.g., measurement reporting, handover command, conditional HO, and failure handling) provide reusable hooks [11]. Beam management and multi-connectivity mechanisms (e.g., beam measurement/reporting, BFR, RA assistance, and multi-TRP or MC operation) can support pre-alignment and continuity [12]. ISAC study items motivate feature/track exchange and air-ground sensing integration [13]. Exact procedures and gains depend on spectrum (FR1/FR2), deployment (single- or multi-TRP), MC availability, and backhaul/edge latency.

TABLE 1. From reactive New Radio (NR) handover to sensing-assisted handover: workflow shift and key ISAC additions (illustrative).

gradually adapting as mobility patterns evolve to maintain stability. Resource placement considers geometric utility, backhaul capacity, and UAV energy availability to ensure practical feasibility. The orchestration cycle operates on a seconds-level timescale and depends on sensing-quality indicators, channel state information, and node energy, reflecting the slower dynamics of network coordination in low-altitude environments.

Design Trade-Offs and Practical Insights

Architectural choices in air-ground collaborative ISAC inherently involve multi-objective trade-offs. In this section, rather than discussing these trade-offs at a purely conceptual level, we translate them into a set of operational guidelines grounded in deployment constraints.

Sensing-Throughput Priority: When airspace density rises and handover failures become the dominant risk, sensing refresh rate should take precedence over throughput, especially in dense urban corridors and emergency routes. In sparse or low-mobility scenarios, throughput-oriented allocation is generally sufficient.

Cooperation Mode Selection: For the cooperation strategy, non-coherent feature-level fusion across multiple UAV viewpoints can serve as the default mode. It offers robust observability with modest synchronization overhead and scales well in practice. Coherent distributed beamforming, which requires strict phase alignment, is justified only when high-precision ranging is required for specific high-value targets or when additional beam gain is necessary to sustain links to fast-moving users. The transition between these modes should be triggered by a feasibility assessment of synchronization conditions rather than fixed configuration rules.

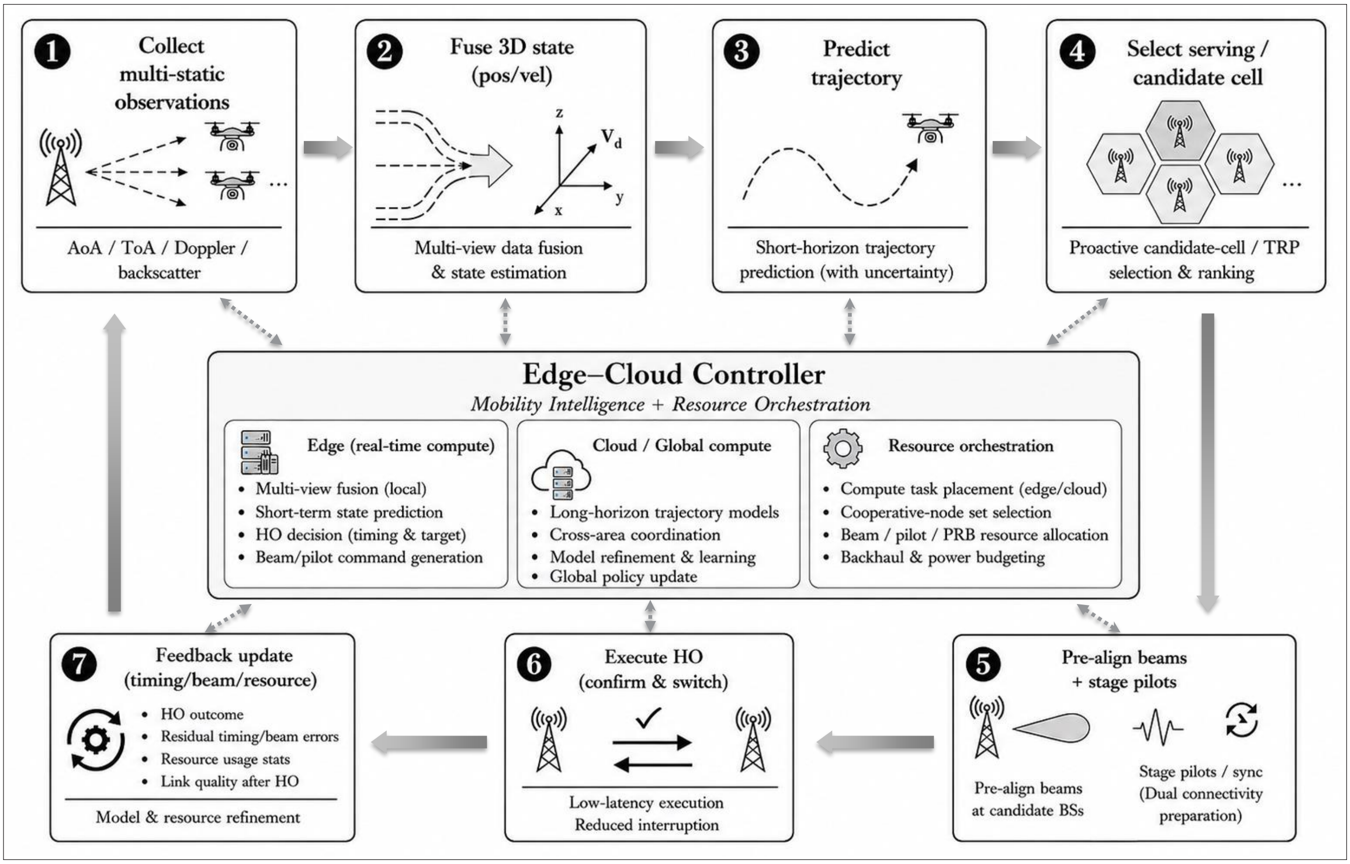

FIGURE 3. Proactive air-ground collaborative ISAC workflow. The system operates in seven steps: (1) multi-static observations from ground and aerial nodes, (2) 3D state estimation via multi-view fusion at the edge/cloud controller, where processing resources are dynamically orchestrated based on latency and mobility-risk requirements, (3) short-horizon trajectory prediction, (4) proactive serving-cell and candidate-cell selection, (5) pre-alignment of beams and pilot staging at candidate BSs, (6) low-latency handover execution, and (7) post-handover feedback for model and resource refinement. Edge computing handles time-critical updates such as track estimation, beam-prior generation, and handover preparation, while cloud computing supports longer-horizon trajectory modeling and cross-area coordination. The loop repeats continuously to enable proactive and seamless mobility for high-speed UAV platforms.

Geometric Diversity First: The cooperative node set should first secure elevation-angle diversity, and only afterward consider channel quality and load. In low-altitude sensing, performance is typically limited by geometric perspective rather than received power. A node offering a distinct altitude view often improves observability more than a nearer node at a similar grazing angle. This ordering establishes geometric coverage before refining the link budget or load balance.

Edge-Centric Control and Targeted UAV Deployment: Handover operates under millisecond-scale latency budgets, making edge-local fusion indispensable on the critical path, while cloud-level processing is better suited for longer-horizon trajectory modeling and cross-area coordination. Accordingly, the edge-cloud partition should adapt to backhaul conditions to balance responsiveness and global consistency. For the same reason, UAV assets should be deployed selectively where air-ground collaboration delivers clear gains, e.g., dense urban areas with severe occlusion, persistent hotspot corridors, or stringent continuity requirements, whereas in open and sparse airspace, coordinated ground infrastructure often suffices and additional UAV deployment may only add energy cost and management complexity.

UAV-supported operation also introduces an energy-endurance trade-off. Continuous sensing, hovering, relaying, and cooperative beamforming consume propulsion, communication, and computation energy, thereby shortening the effective mission duration of aerial nodes. Hence, UAV participation should be activated selectively in regions where the expected mobility or sensing gain justifies the endurance cost, and cooperative sets should be updated according to both geometric utility and residual energy.

Beyond performance gains, the cooperative architecture also enhances system resilience. Multi-perspective observations enrich physical-layer features and create cross-validation opportunities that can provide anomaly cues for detection and verification [14]. For instance, a falsified position report that must remain geometrically consistent across multiple spatially separated and independently operated observation nodes is more difficult to fabricate than spoofing a single viewpoint. However, this resilience benefit relies on the critical assumptions that observation nodes are independently controlled, synchronization references are trustworthy, and the attacker cannot simultaneously compromise multiple distributed platforms. These cross-consistency checks offer a complementary anomaly-detection layer but do not constitute a security guarantee and must be combined with cryptographic authentication and integrity protection mechanisms.

The limitations of this work are worth noting. The framework provides limited benefit in open or sparsely covered airspace and may be constrained by UAV energy, control, or regulatory requirements. Additionally, mobility gains can be reduced when trajectory predictions are unreliable, backhaul is delayed, synchronization errors occur, or multiple observation links are simultaneously blocked. In such situations, conventional ground-based procedures remain more reliable option.

Open Challenges and Future Work

Air-ground collaborative ISAC raises a set of inter-related engineering challenges that should be addressed before large-scale deployment becomes practical. In this section, we highlight four major directions that merit further investigation.

Synchronization and Phase Coherence: Cooperative beamforming and multi-static sensing rely on tight time and phase alignment across ground BSs and UAVs. Although GNSS offers a baseline timing source, its reliability degrades in dense urban environments. Therefore, alternative over-the-air synchronization mechanisms are required to achieve comparable robustness. In addition, relative motion among aerial nodes introduces Doppler shifts that erode beamforming gains without accurate tracking, making autonomous phase tracking under mobility an open problem.

Near-Field Calibration and Online Adaptation: In near-field regimes, particularly for mobile aerial arrays, the array response becomes highly sensitive to both positional displacement and orientation variation. Although several online calibration techniques have been proposed, their capability remains limited in dynamically evolving scenarios [7]. As UAVs maneuver, the underlying array manifold continuously changes, requiring real-time estimation and compensation. Achieving this adaptability without incurring prohibitive training overhead or disrupting mission-critical operations remains a significant challenge.

Robust Tracking in Urban Occlusion: In dense urban environments, building-induced blockage can disrupt multi-static sensing chains, even when aerial platforms provide elevated vantage points. Such intermittent visibility fundamentally challenges continuous tracking. As a result, prediction and filtering algorithms should remain resilient to occlusion-induced outages, gracefully degrading to alternative estimation modes as line-of-sight conditions fluctuate. This resilience demands the integration of pre-computed terrain or city models with real-time visibility inference, enabling proactive rather than purely reactive tracking adaptation. Performance under varying prediction accuracy and coordination conditions remains to be validated in detailed simulations or experiments.

Standardization and 6G Integration: Existing standards have yet to define end-to-end mechanisms that tightly integrate air-ground sensing with mobility control [13]. Bridging this gap requires more than incremental protocol extensions. Key open issues include reference signal designs tailored for multi-static sensing, cooperative control-plane message formats enabling cross-platform coordination, and well-defined fusion interfaces that decouple sensor processing from mobility decision logic. Beyond technical enablers, standardized frameworks must also address trajectory-data privacy and cross-domain security, ensuring trustworthy cooperation across heterogeneous platforms in emerging 6G ecosystems.

Conclusion

In this article, we addressed the 3D observability gap in low-altitude networks and proposed an air-ground collaborative ISAC architecture in which UAV swarms operate as VAAs to introduce elevation diversity and enhance mobility awareness. By integrating cooperative beamforming, sensing-assisted handover, and dynamic resource orchestration, the framework transforms mobility management from reactive recovery into predictive preparation. The resulting design improves robustness, service continuity, and geometric conditioning in dense and dynamic airspace, while providing practical deployment guidelines for future 6G-enabled low-altitude networks. In addition, we discussed key design insights and identified open research challenges to guide further development and standardization of air-ground collaborative ISAC systems.

Acknowledgment

N. Su would like to acknowledge the financial support of the NSFC under Grant 62401181 and the Research Matching Grant Scheme from the Research Grants Council of Hong Kong. X. Jing has received funding from Dongguan Strategic Scientist Teams Project under Grant 20241900700013 and National Natural Science Foundation of China, No. 62501153. The work of Q. Zhang has been supported by the Major Key Project of PCL of China (No. PCL2024A01) and the NSFC under Grant 62027802. The work of T.-T. Chan was supported in part by the Research Matching Grant Scheme from the Research Grants Council of Hong Kong.

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