UAV-Empowered Integrated Sensing and Communication for 6G

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Abstract

Uncrewed aerial vehicle (UAV)-aided integrated sensing and communication (ISAC) is envisioned to play an increasing important role in sixth-generation (6G) mobile communication systems, where the UAVs can serve as an aerial base station to extend the network coverage and provide improved sensing and communication services for mobile users. Compared to terrestrial base stations, UAVs exhibit distinct attributes (i.e., line-of-sight links, controllable mobility, restricted endurance, etc.) introduces both opportunities and challenges to improve the ISAC performance. To shed light on future research trends, this paper provides a comprehensive survey for UAV-aided ISAC. We firstly introduce the hierarchical network architecture, unique performance advantages, and typical applications of UAV-aided ISAC. Then, we present the key techniques including ISAC frame design, waveform design, UAV deployment optimization, operational mode, and resource management to reveal how to achieve UAV-aided ISAC. Next, a case study is provided to demonstrate the performance advantages of UAV-aided ISAC. Finally, some existing design challenges and open issues are elaborated to provide the guidance for future works.

I. Introduction

In 6G era, sensing will play a critical role to support various emerging applications, such as autonomous driving, smart cities, industrial internet of things, and so forth. Beyond high-performance communication services, such applications generally require real-time environmental sensing. Moreover, due to the rapid increase of mobile devices, the restricted spectrum resource is envisioned as the main design bottleneck to satisfy ever-increasing sensing and communication requirements in future 6G [1]. To tackle this design challenge, ISAC is recognized as an effective approach, where hardware equipment and spectral resources are shared at the base stations (BS) to conduct target sensing and information transmissions simultaneously [2].

Furthermore, 6G is expected to achieve ubiquitous and seamless network coverage. Nevertheless, in the unexpected or emergency situations (e.g., earthquake, flood, temporal hotspot areas, etc.), the deployment of terrestrial BSs will be extremely challenging and economically infeasible due to the complex geographical environments and high operational cost [3]. In such scenarios, the communication and sensing requirements of mobile users cannot be ensured, and it will further restrict the deployment and promotion of emerging applications in remote and hard-to-reach regions. Benefited from low-cost and flexible deployment, UAV-aided ISAC is a promising technique to provide ubiquitous sensing and communication services for mobile users in conjunction with terrestrial networks, where UAVs serve mobile users in the scenarios without terrestrial BSs.

Unlike terrestrial ISAC systems, several design challenges still exist in UAV-aided ISAC. First, UAVs are fundamentally limited by their weight, size and battery capacity, which further imposes great restrictions on their sensing, communication and endurance abilities. Second, the flexible mobility of UAV brings additional degree of freedoms to improve the communication rate and sensing accuracy, which also makes the system optimization problem extremely challenging considering the dynamic network environments and heterogeneous sensing/communication requirements. Third, unlike terrestrial networks with non-negligible blockage and shadow fading, UAV has remarkably higher probabilities to construct line-of-sight (LoS) air-ground/air-air links that can improve the ISAC performance, while it also introduces severe co-channel interference and information leakage risks. Fourth, UAVs are prone to horizontal and longitudinal jitters caused by wind disturbances. Such jitter phenomenon will lead to the deviation of sensing/communication beams, and further degrade the ISAC performance. Finally, different from the conventional UAV-aided communications/sensing focusing on optimizing separated sensing/communication performance, UAV-aided ISAC needs to achieve the optimal balance between sensing and communications, which involve the design of new frame structure, transmit waveforms and resource management strategies.

To tackle the aforementioned research challenges, it is essential to establish a unified theoretical

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and design framework for UAV-aided ISAC systems. Accordingly, this paper provides a comprehensive survey that systematically reviews recent research progress and key enabling technologies in this emerging area. Specifically, Section II introduces the three-layer network architecture of UAV-aided ISAC and highlights its unique performance advantages and representative applications. Section III illustrates the key techniques of UAV-aided ISAC, including frame structure, waveform design, UAV deployment optimization, operational modes, and resource management. Section IV presents a case study to demonstrate the performance advantages of UAV-aided ISAC. Subsequently, Section V discusses several open research issues related to energy sustainability, robust system design, security, and intelligent scheduling. Finally, Section VI concludes this paper.

It is worth noting that previous surveys [2], [3] mainly focus on signal processing techniques and cooperative sensing in UAV-aided ISAC systems, whereas [4] provides a review of cellular-connected UAV-ISAC systems by discussing the UAV's dual roles as both a sensing target and an aerial sensing/communication platform. In contrast, this paper aims to provide a holistic and multi-layer perspective that bridges physical-layer signal design with system-level deployment and optimization theories, thereby offering integrated insights and practical guidelines for future research and applications of UAV-aided ISAC.

II. UAV-ISAC Framework

In this section, we present the hierarchical network architecture, performance advantages, and typical applications of UAV-aided ISAC.

A. Hierarchical Network Architecture

Fig. 1 shows the overall network framework, which is divided into three layers, i.e., ground layer, air layer, and space layer. In addition, software defined network (SDN)-based control center is deployed to perform network deployment optimization and resource management in a flexible and efficient manner.

1) Ground Layer: Regarding the ground layer, heterogeneous wireless access networks (e.g., macro cells, micro cells, etc.) are deployed to serve a variety of mobile devices, including mobile phones, wearable devices, sensor devices, smart vehicles, etc.In general, ground networks provide efficient radar sensing and communication services for mobile users in urban areas. However, their coverage in remote regions is limited by high deployment costs, and the service quality in temporary hotspot areas cannot be consistently guaranteed. For instance, a large number of athletes, reporters and audience will pour into main stadium during the opening of sport games. The ground BSs are incapable of handling the sudden surge in service demands caused by the proliferation of mobile devices.

2) Air Layer: The air layer encompasses diverse uncrewed flying platforms, including UAVs, balloons, and airships, which offer heterogeneous sensing and communication capabilities. Based on their flight altitudes, these aerial systems are typically classified into low-altitude platforms (LAPs) and high-altitude platforms (HAPs). Their coverage ranges are further influenced by factors such as transmit power and environmental conditions. Moreover, these aerial platforms are installed with transceivers to provide information transmissions and radar sensing services for mobile users in the scenarios without terrestrial BSs, such as emergency rescues, environmental monitoring, and so forth. Compared to terrestrial BSs, unscrewed aerial platforms exhibit distinct advantages including LoS links, flexible mobility, and ease of deployment. Consequently, UAV-aided ISAC can also be exploited to enhance the service quality of mobile users in temporal hotspot areas. Besides, in order to enhance the coverage area and sensing/communication capability, multiple UAVs can be grouped into a UAV swarm for conducting cooperative target sensing and information transmissions. Moreover, UAVs are equipped with heterogeneous radio interfaces (e.g., WiFi, long term evolution, etc.) to communicate with satellites and ground BSs.

Recently, several real-world deployment cases and experimental testbeds have demonstrated the feasibility of aerial flying platform-aided ISAC systems. For instance, Beuster et al. [5] developed a 3.75 GHz UAV localization testbed that enables high-precision radar-assisted UAV tracking in complex propagation environments. The system achieved sub-meter localization accuracy and verified efficient waveform sharing between sensing and communication.

3) Space Layer: In the space layer, various types of satellites are deployed to realize global coverage. According to the distance between the satellite and earth, satellite orbits are divided into low earth orbit (700-2000 km), medium earth orbit (8000-20000 km), and geostationary earth orbit (35786 km). Satellites located at different orbits and inter-satellite links construct a global space-based information network. With the recent advancement of hardware circuits and signal processing technique, space layer is able to provide ISAC services for both air and ground layers. However, the satellite-to-ground links suffer from the large free-space path loss and tropospheric attenuation significantly. Meanwhile, the channel of satellite-to-UAV links mainly depends on the LoS component and also suffers from the tropospheric attenuation. Due to the long space-air and space-ground transmission distance, the space network cannot be used to ensure the service quality for delay-sensitive applications, such as autonomous driving, etc.

B. Performance Advantages of UAV-Aided ISAC

UAV-aided ISAC is envisioned as a candidate technique in 6G due to the following performance advantages:

1) Beyond LoS Sensing and Communication: Benefiting from their mobility, UAVs excel in beyond LoS sensing and communication by accessing areas that are inaccessible or not visible to fixed terrestrial BSs. Moreover, their high operating altitudes and the open aerial environment enable the establishment of reliable LoS air-to-ground and air-to-air links, thereby facilitating high-performance radar sensing and communication.

2) Seamless Sensing and Communication: Due to the advantages of low-cost and flexible deployment, UAVs can be released to provide radar sensing and communication services in remote or hard-to-reach regions without terrestrial BSs. Moreover, UAV-aided ISAC can be used to tackle some scenarios with sudden and unexpected service requirements, such as emergence rescue and temporal hotspot areas. Based on these observations, UAVs and terrestrial BSs will cooperate with a complementary manner to provide seamless sensing and communication services for mobile users.

3) Multi-UAV Cooperative Sensing and Communication: In UAV-aided ISAC, multiple UAVs can cooperatively transmit downlink signals for conducting joint radar sensing and information transmissions, forming a distributed large-scale antenna array in the sky. Compared with terrestrial multi-node cooperation, such multi-UAV collaboration offers flexible three-dimensional deployment and adaptive array configurations, thereby enhancing LoS connectivity, mitigating co-channel interference, and improving both sensing accuracy and communication rate.

4) Service Continuity: In 6G era, a variety of high-speed mobile applications will be deployed to improve our daily life, such as high-speed railway, autonomous driving, etc. For such high-speed applications, the frequent handover of terrestrial BSs will greatly degrade the service experience of mobile users. Integrated aerial platforms into these applications, mobile devices can enjoy the enhanced sensing/communication services provided by aerial platforms with a significantly larger coverage area for reducing the frequent handover. Furthermore, the aerial platform can adjust its moving trajectory to follow the mobile users for ensuring the service continuity.

C. Potential Applications for UAV-Aided ISAC

Due to its distinct performance advantages, UAV-aided ISAC holds great potential to support a variety of emerging applications, including emergency rescue, Internet of Vehicles (IoVs), temporal hotspots, and so on.

1) Emergence Rescue: In disaster scenarios, establishing efficient information exchange networks is crucial for supporting emergency rescue operations during the initial hours. However, terrestrial BSs may be completely destroyed by severe natural disasters, such as earthquakes or floods. In such cases, UAV-aided ISAC can play a vital role due to its low-cost and flexible deployment. On one hand, UAVs can perform environmental sensing to guide rescue efforts. On the other hand, they can serve as aerial BSs to ensure reliable information transmission to wireless terminals.

2) IoVs: In IoVs, the real-time target sensing and information transmissions are crucial to avoid terrible traffic accidents. For example, accurately perceiving surrounding vehicles and objects is essential to ensure the safe operation of autonomous driving systems. Given the high mobility of vehicles, only depending on terrestrial BSs is insufficient to satisfy the strict sensing and communication requirements of intelligent vehicles. Exploiting the flexible mobility of UAVs, aerial platforms can be deployed for enhancing the sensing/communication ability in IoVs.

3) Temporal hotspots: In temporal hotspots, there exist a large number of mobile devices with diverse communication and sensing requirements. For example, during the opening ceremony of sports games, massive audiences gather in the stadium, leading to a surge in service demands. The ground BSs are often incapable of handling such sudden increases in traffic caused by the proliferation of mobile devices. To tackle this problem, UAV-aided ISAC can be employed to assist terrestrial networks by performing part of the sensing and communication tasks in these temporal hotspot areas.

4) Embodied and Swarm Intelligence Systems: In future intelligent systems, embodied intelligence relies on the efficient integration of sensing, communication, computation, and control within physical entities. UAV-aided ISAC provides a versatile platform to support this goal. With joint sensing and communication capabilities, UAVs can collaboratively perceive their surroundings to achieve real-time awareness and adaptive decision-making. Meanwhile, by serving as aerial communication and computing nodes, UAVs enable high-rate data exchange, distributed information processing, and coordinated control. Such cooperation forms a swarm-intelligent architecture in which UAVs dynamically adapt their sensing and communication strategies. Therefore, UAV-aided ISAC serves as a pivotal technology for realizing embodied and swarm intelligence by establishing a tight coupling among sensing, communication, computation, and control.

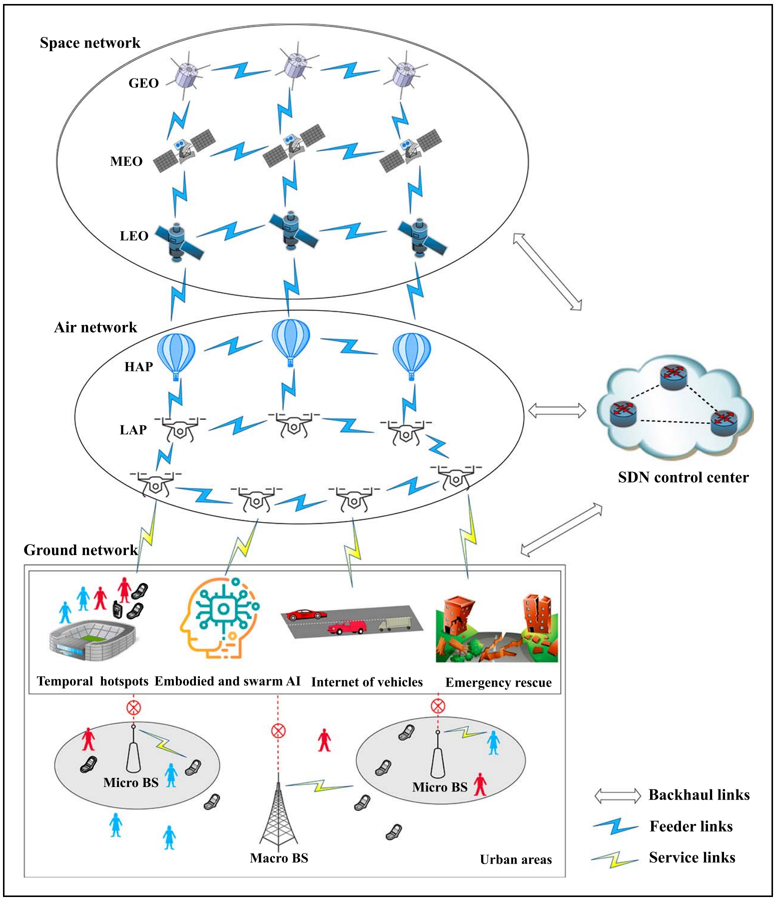


FIG. 1. Hierarchical architecture including space, air, and ground networks.

III. Key Technologies for UAV-Aided ISAC

In this section, we summarize the key technologies for empowering UAV-aided ISAC from the following five aspects, i.e., ISAC frame design, ISAC waveform design, UAV deployment optimization, operational mode of UAV-aided ISAC, and resource management.

A. ISAC Frame Design

In order to coordinate the radar sensing and communication, several types of ISAC frame have been proposed consisting of co-ISAC frame, TDM-ISAC frame, and hybrid-ISAC frame [6], which are shown in Fig. 2.

1) Co-ISAC Frame: In this protocol, all targets are sensed simultaneously within each time slot while information transmission to all communication nodes

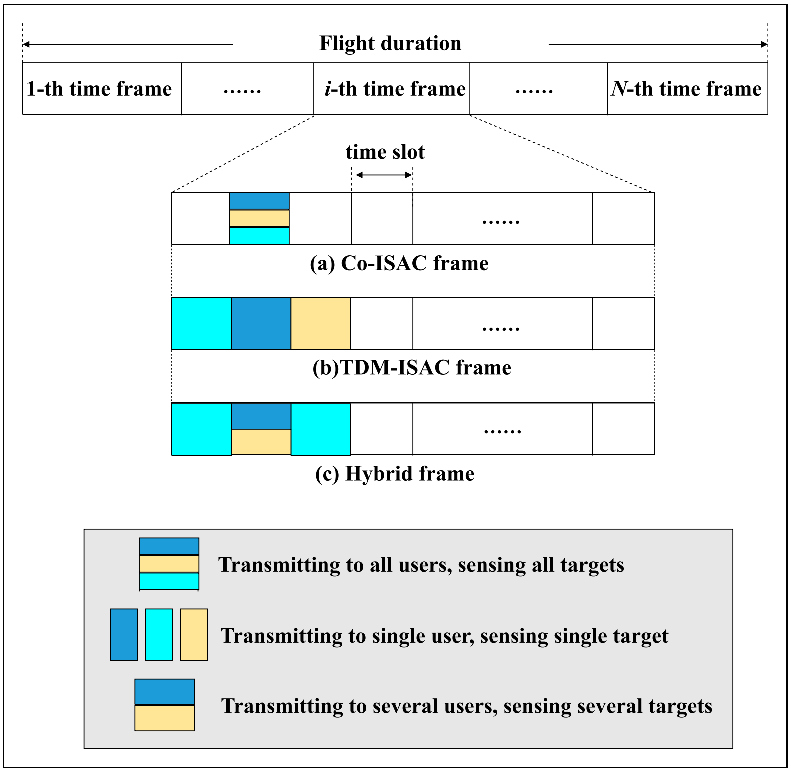


FIG. 2. ISAC Frame: (a) Co-ISAC frame enabling simultaneous radar sensing and data transmission for all nodes, (b) TDM-ISAC frame separating sensing and communication over orthogonal time slots, and (c) Hybrid frame combining Co-ISAC and TDM-ISAC frames.

occurs concurrently. Consequently, the ISAC beams must be jointly optimized to cover all sensing targets and communication nodes. However, the Co-ISAC frame is inherently affected by co-channel interference, which can significantly degrade both sensing and communication performance. This challenge is further pronounced in UAV-aided ISAC systems due to the high probability of LoS links, which amplify mutual interference among spatially aligned beams. To mitigate this issue, the UAVs' hovering positions and the ISAC beams should be jointly designed to balance sensing coverage and communication quality.

2) TDM-ISAC Frame: In this protocol, radar sensing and information transmission for multiple targets or communication nodes are performed in a time-division manner. Each time slot is dedicated to one sensing target and one communication node to reduce harmful co-channel interference. Nevertheless, echoes from other targets may still introduce undesired interference, which can degrade sensing accuracy. For UAV-aided ISAC systems, trajectory optimization plays a vital role in sequentially covering distributed communication nodes and sensing targets. Such optimization not only satisfies the performance requirements of sensing and communication but also minimizes energy consumption, which is essential considering the limited battery capacity of UAVs. Furthermore, the time-varying network topology introduced by UAV controllable mobility can be effectively exploited to enhance spatial diversity and sensing accuracy.

3) Hybrid-ISAC Frame: This protocol integrates the advantages of Co-ISAC and TDM-ISAC frames. Targets are partitioned into multiple groups based on their geographic distribution. Co-ISAC operations are applied within each group while TDM-ISAC is employed across groups. In UAV-aided ISAC systems, grouping schemes and trajectory planning are closely coupled. The UAV can dynamically reposition to form or adjust groups according to spatial correlation and mission priorities. This hybrid design achieves an effective trade-off between ISAC performance and design complexity, and it exploits UAV mobility to ensure reliable coverage and high operational efficiency.

B. ISAC Waveform Design

In UAV-aided ISAC systems, the advanced waveform design holds great potential to eliminate the harmful co-channel interference between the radar sensing and information transmissions. Generally speaking, ISAC waveform can be divided into three categories, i.e., communication-centric waveform, radar-centric waveform, and joint waveform [7]. For ease of exposition, Table I summarizes and compares the three representative ISAC waveforms.

1) Communication-centric Waveform Design: The key idea of communication-centric waveform is to utilize and modify classic communication waveforms to achieve the radar sensing at the same time, and the sensing information can be extracted from the signal echoes reflected by sensing targets. In such a design, the communication performance is generally unaffected, and almost all the communication waveforms are exploited to achieve the radar sensing. In general, a large portion of classic communication waveforms can be directly exploited including orthogonal frequency division multiplexing (OFDM), single carrier, index modulation (IM), orthogonal time frequency space (OTFS), etc.

2) Radar-centric Waveform Design: Radar-centric waveform design is to exploit the radar waveforms to support the information transmissions simultaneously. In general, the radar waveforms contain no communication information. Therefore, in radar-centric waveform design, the communication information need to be embedded into the radar waveform to enable target sensing and information transmissions simultaneously. Based on the information-embedding approach, radar-centric waveform design is divided into three categories including information embedded in spatial domain, information embedded based on index modulation, and information embedded based on chirp waveform [2].

3) Joint Waveform Design: Joint waveform design aims to jointly optimize the ISAC waveforms through different performance metrics, such as signal to interference plus noise ratio (SINR), Cramér-Rao bound (CRB), mutual information, etc. Since the joint waveform design utilizes no existing waveforms, it exhibits higher flexibility to balance the sensing and communication performance. In UAV-empowered ISAC systems, joint waveform design must take into account UAV trajectory planning, time-varying channel characteristics induced by UAV mobility, and energy-aware waveform adaptation, so as to ensure sustainable operation throughout the mission.

C. UAV Deployment Optimization

In UAV-aided ISAC systems, optimizing UAV deployment plays a crucial role in enhancing sensing coverage, communication quality, and energy efficiency through flexible three-dimensional positioning and mobility control. In general, UAV deployment strategies can be classified into three types, namely

Waveforms	Design Principles	Advantages	Limitations
Communication-centric waveform	Utilizing existing communication waveforms for sensing.	· Direct compatibility with current communication standards (e.g., OFDM, IM, OTFS). · High spectral efficiency for data transmission.	Limited sensing accuracy due to the absence of dedicated radar features.
Radar-centric waveform	Exploiting existing radar waveforms for communication.	· High-resolution target detection and parameter estimation. · Leveraging mature radar signal processing techniques.	Restricted data transmission rate.
Joint waveform design	Designing ISAC waveforms by optimizing either communication or sensing performance while satisfying constraints imposed by the other.	Facilitating a flexible trade-off between communication and sensing performance.	Increased design and implementation complexity.

TABLE I. Comparison of ISAC waveform design approaches.

hovering mode, flying mode, and hybrid mode, as illustrated below.

1) Hovering Mode: In the hovering mode, multiple UAVs remain stationary at predefined positions to simultaneously conduct radar sensing and communication. The optimal hovering locations and ISAC beamforming should be jointly optimized to satisfy the dual requirements of sensing and communication. In [8], Lyu et al. formulated a weighted sum-rate maximization problem subject to minimum sensing beampattern gain constraints. They demonstrated that optimal UAV placement is crucial for balancing sensing accuracy and communication throughput. Although the hovering mode avoids additional flight energy consumption, its static nature restricts the the system adaptability to dynamic service requirements.

2) Flying Mode: In the flying mode, UAV trajectories are dynamically optimized to accommodate spatiotemporally varying sensing and communication requirements. As expected, this mode can be discretized into a series of hovering position optimization subproblems by dividing the operation period into sufficiently small time slots, during which the UAV is assumed to remain quasi-static. Compared with the hovering mode, the flying mode enables more flexible spatial deployment and thus achieves higher ISAC efficiency. However, it also results in greater flight energy consumption and increased trajectory planning complexity.

3) Hybrid Hovering and Flying Mode: To balance the advantages and drawbacks of both hovering and flying modes, a hybrid deployment strategy can be adopted. As analyzed in [9], the aerodynamic power of a UAV consists of induced, profile, and parasitic drag components, which are determined by its specific flight state. During hovering, aerodynamic power is primarily dominated by induced and profile power, with parasitic drag being negligible, making hovering near sensing targets or communication nodes energetically advantageous. In horizontal flight, parasitic drag increases cubically with velocity, in addition to profile and induced power, indicating that flight paths should be short, direct, and operated at moderate speeds. Based on these observations, for UAV-aided ISAC networks covering distributed communication nodes and sensing targets, a hybrid deployment strategy that combines hovering at key points with flight across multiple distributed nodes and targets can efficiently balance sensing/communication performance with overall energy consumption.

D. Operational Mode of UAV-Aided ISAC

In UAV-aided ISAC, the operational model includes separated mode, cooperative mode, and hybrid mode.

1) Separated Mode: In this mode, UAVs perform sensing and communication tasks in a separate manner. As shown in Fig. 3(a), from the aspect of communication, the UAV and its associated users will suffer from severe co-channel interference from the information transmissions of adjacent UAVs and users. In particular, the LoS dominant air-air and air-ground channels make the interference problems even more terrible. From the aspect of sensing, the two-link echo signal for radar sensing experiences the interference from single-link transmit signals of adjacent UAVs and users. Therefore, it is crucial to design efficient countermeasures to tackle such interference.

2) Cooperative Mode: In the cooperative mode, as illustrated in Fig. 3(b), multiple UAVs perform radar sensing and information transmission collaboratively to enhance the overall performance of UAV-aided ISAC systems. From the communication perspective, the virtual array gain enabled by cooperative multi-UAV transmissions can effectively mitigate harmful interference and improve spectral efficiency. From the sensing perspective, multiple UAVs can jointly conduct radar sensing to extend coverage and enhance sensing accuracy. Nevertheless, precise clock synchronization among cooperating UAVs is essential to prevent performance degradation in multi-UAV cooperative sensing and communication.

3) Hybrid Mode: Although the benefits brought by the cooperative mode, it also introduces high signal processing complexity and strict synchronization requirements. Therefore, as shown in Fig. 3(c), the hybrid mode is recognized as a suitable solution to balance the sensing/communciation performance and design complexity, in which a part of UAVs work in cooperative mode, and the others operate in separated mode. In this mode, it is important to select proper UAVs to conduct cooperative sensing and communications.

E. Resource Management

Resource management is a critical component in UAV-aided ISAC systems, as UAVs are typically subject to stringent constraints on communication and

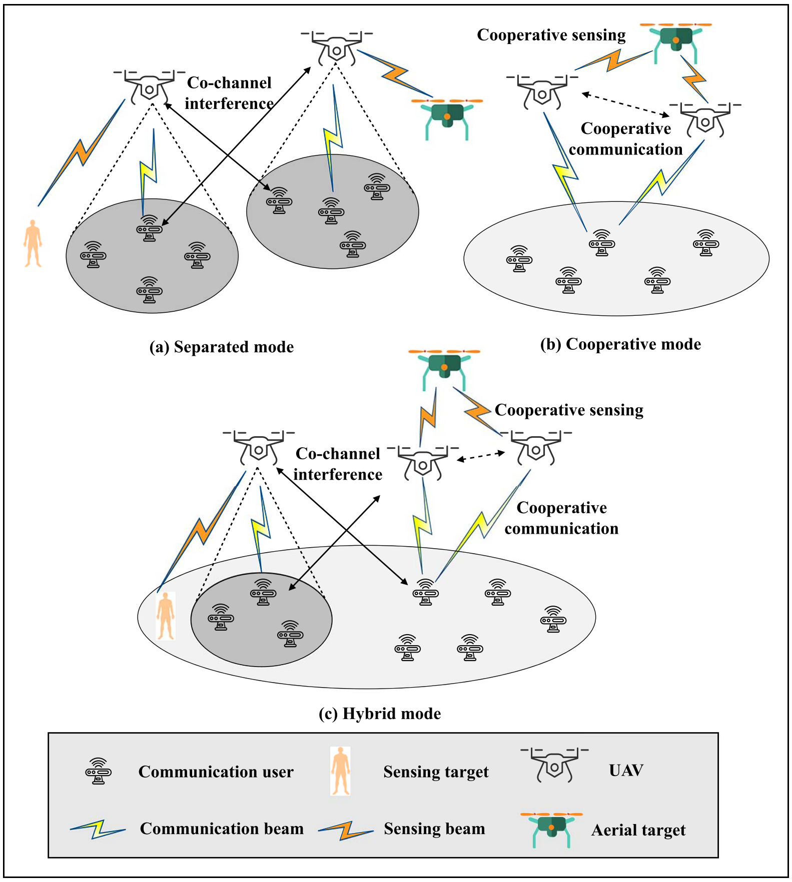


FIG. 3. Operational mode of UAV-aided ISAC: (a) Separated mode with independent sensing and communication, (b) Cooperative mode with joint multi-UAV operations, and (c) Hybrid mode integrating separated and cooperative modes.

sensing capability, as well as energy endurance. However, the inherently conflicting design objectives of sensing and communication, together with the strong coupling between UAV mobility control and multi-dimensional resource allocation, make the joint optimization problem highly challenging. Existing literature on resource management for UAV-aided ISAC systems can be broadly categorized into two classes: model-driven approaches and learning-driven approaches.

1) Model-Driven Resource Management: Model-driven approaches typically formulate mathematically tractable frameworks to optimize specific performance objectives, such as maximizing the sum rate, minimizing power consumption, or improving sensing accuracy. In [8], [10], the authors investigated joint UAV trajectory and transmission optimization strategies to enhance communication throughput while satisfying desired sensing beampattern constraints. Wu et al. [11] employed Kalman filtering to predict the motion states of sensing targets and derived the corresponding CRB from these estimates, based on which a joint trajectory scheduling and association control algorithm was developed to balance sensing accuracy and communication performance. Similar to mutual information to evaluate the information bit, sensing mutual information measures the environmental information contained in the echo signals. In [12], Ouyang et al. investigated the mutual information-based optimization framework for ISAC. They further revealed the performance of downlink and uplink ISAC systems, and quantified the performance gap between ISAC and frequency-division sensing and communication schemes. Furthermore, total cost minimization have been integrated into UAV-aided ISAC design. For example, Liu et al. [13] aimed to minimize the weighted sum of energy consumption and latency in UAV-aided ISAC for IoV networks.

Although model-driven methods provide solid theoretical foundations and valuable design insights, they often suffer from high computational complexity, limited scalability, and poor adaptability to dynamic network environments (e.g., random channel variations and user mobility). Moreover, their strong reliance on accurate system modeling considerably restricts their applicability in practical UAV-aided ISAC scenarios.

2) Learning-Driven Resource Management: Benefiting from their ability to interact with dynamic environments, deep reinforcement learning (DRL) techniques have demonstrated strong potential for adaptive trajectory planning and resource management in UAV-aided ISAC systems. In [14], Gao et al. developed a DRL-based framework that jointly optimizes UAV trajectory and beamforming to maximize the communication sum rate under sensing beampattern constraints. Huroon et al. [15] further employed reconfigurable intelligent surfaces (RISs) to enhance UAV-aided ISAC and proposed a multi-agent DRL framework for joint trajectory and resource optimization, aiming to improve both sensing signal-to-noise ratio and communication throughput. Simulation results demonstrated that DRL-based methods achieve superior ISAC performance while substantially reducing computational complexity compared with conventional model-driven approaches.

Based on above descriptions, resource management in UAV-aided ISAC has evolved from model-driven optimization to learning-driven strategies. This transformation improves adaptability and scalability, laying a solid foundation for real-time mobility optimization and intelligent resource coordination in UAV-aided ISAC networks.

IV. Case Study: DRL-Based Joint Beamforming and Trajectory Optimization for UAV-Aided ISAC

In this section, we present a case study on DRL-based joint beamforming and trajectory optimization method for UAV-aided ISAC, aiming to demonstrate both the performance advantages of UAV-aided ISAC and the adaptability enhancement brought by DRL.

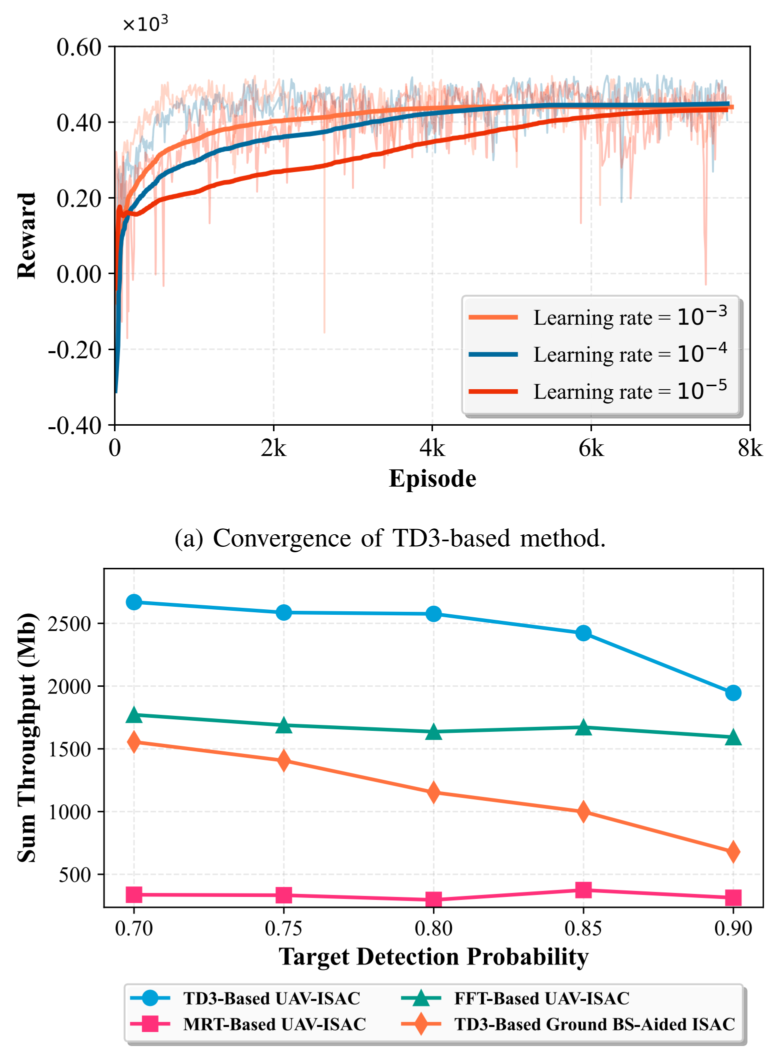
1) Parameter Setup: We consider a representative UAV-aided ISAC scenario consisting of one UAV, two communication users, and one sensing target. The coordinates of the communication users and the sensing target are set to ([25m, 75m, 0m], [75m, 75m, 0m]) and [50m, 25m, 0m], respectively. The UAV is equipped with a uniform linear array of eight antennas, where four antennas are dedicated to communication and the remaining four are allocated for sensing. The UAV flies at a fixed altitude of 50 meters with a maximum horizontal velocity of 15 m/s. The duration of each time slot and the total mission time are set to 0.25 s and 40 s, respectively. The air-to-ground channels are assumed to be LoS dominated, with a path loss of −30 dB at unit distance. The noise power at each communication user and the UAV receiver is set to −84 dBm and −102 dBm, respectively.

Meanwhile, the twin delayed deep deterministic policy gradient (TD3)-based DRL method is exploited to solve the joint trajectory and beamforming optimization problem for considered UAV-aided ISAC system. The reward function integrates two key performance metrics. The first is energy efficiency, measured as the ratio between the total system throughput and the UAV's energy consumption. The second is target detection reliability, which requires the detection probability to remain above a specified threshold to ensure sensing performance. Accordingly, the reward is defined as Reward $= \eta_1 E + \eta_2 P$, where η_1 and η_2 denote weighting coefficients, E represents the energy efficiency, and P denotes the penalty term. Specifically, P is set to 1 when the achieved target detection probability satisfies the threshold; otherwise, P is equal to 10 times the difference between the achievable target detection probability and the predefined threshold.

2) Benchmark Methods: For comparison, three benchmark schemes are considered: 1) Fixed Flying Trajectory (FFT)-Based UAV-ISAC: The UAV moves at a constant velocity along a predefined straight path from the starting point to the ending point, while beamforming is optimized utilizing the TD3-based DRL algorithm; 2) TD3-Based Ground BS-Aided ISAC: A terrestrial BS conducts both downlink communication and target sensing, where the radar and information beamformers are optimized through the TD3-based DRL approach; 3) Maximum Ratio Transmission (MRT)-Based Scheme: The UAV adopts MRT beamforming for both communication and sensing, while its flight trajectory is optimized via the TD3-based DRL algorithm.

3) Performance Evaluation of DRL-Based UAV-ISAC: Fig. 4(a) illustrates the convergence behavior of the proposed TD3-based method under different learning rates. It can be observed that the reward achieved by the TD3-based algorithm is initially low due to the lack of prior experience. As the number of training episodes increases, the accumulated reward grows rapidly and converges after approximately 5000 episodes. This result indicates that the TD3 agent effectively learns a stable beamforming and trajectory optimization policy through sufficient training.

Fig. 4(b) presents the relationship between the target detection probability threshold and the total throughput. It is observed that the total throughput decreases as the detection probability threshold increases, since more transmission power must be allocated for sensing, leaving less available power for communication. Additionally, the proposed TD3-based UAV-aided ISAC scheme achieves a significantly larger communication-sensing performance region compared to all benchmark methods. This improvement arises from its ability to adaptively optimize the UAV's trajectory and beamforming strategy in response to dynamic channel conditions, thereby maintaining an effective balance between sensing and communication performance.



(a) Convergence of TD3-based method.

(b) Sum throughput versus target detection probability.

FIG. 4. Performance evaluation of DRL-based UAV-ISAC: (a) Convergence of TD3-based method under different learning rate, and (b) Performance comparison of TD3-based UAV-ISAC with existing benchmark methods.

V. Design Challenges and Open Issues

Despite the significant potential of UAV-aided ISAC, several design challenges and open research issues remain to be addressed for its practical implementation.

A. Service Sustainability of UAV-Aided ISAC

Unlike terrestrial BSs with stable energy supply, UAV-aided ISAC is fundamentally restricted by limited battery capacity of UAVs. In addition, except for the conventional flying energy consumption, the non-negligible radar sensing and communication energy consumption exacerbate the energy shortage problem of UAV. Therefore, how to prolong the lifetime of UAV to ensure the service sustainability is recognized as an important research topic for UAV-aided ISAC systems. To tackle this issue, on the one hand, it is essential to design energy-efficient trajectory optimization and transmission strategies for balancing ISAC performance and UAVs' energy consumption. On the other hand, as illustrated in Fig. 5(a), hybrid energy-powered UAVs have emerged as a promising solution. In addition to onboard batteries, UAVs are equipped with renewable energy harvesting devices, such as solar panels, to extend their operational endurance. In this context, it is essential to jointly optimize the sensing and communication performance while maintaining the energy sustainability of UAVs.

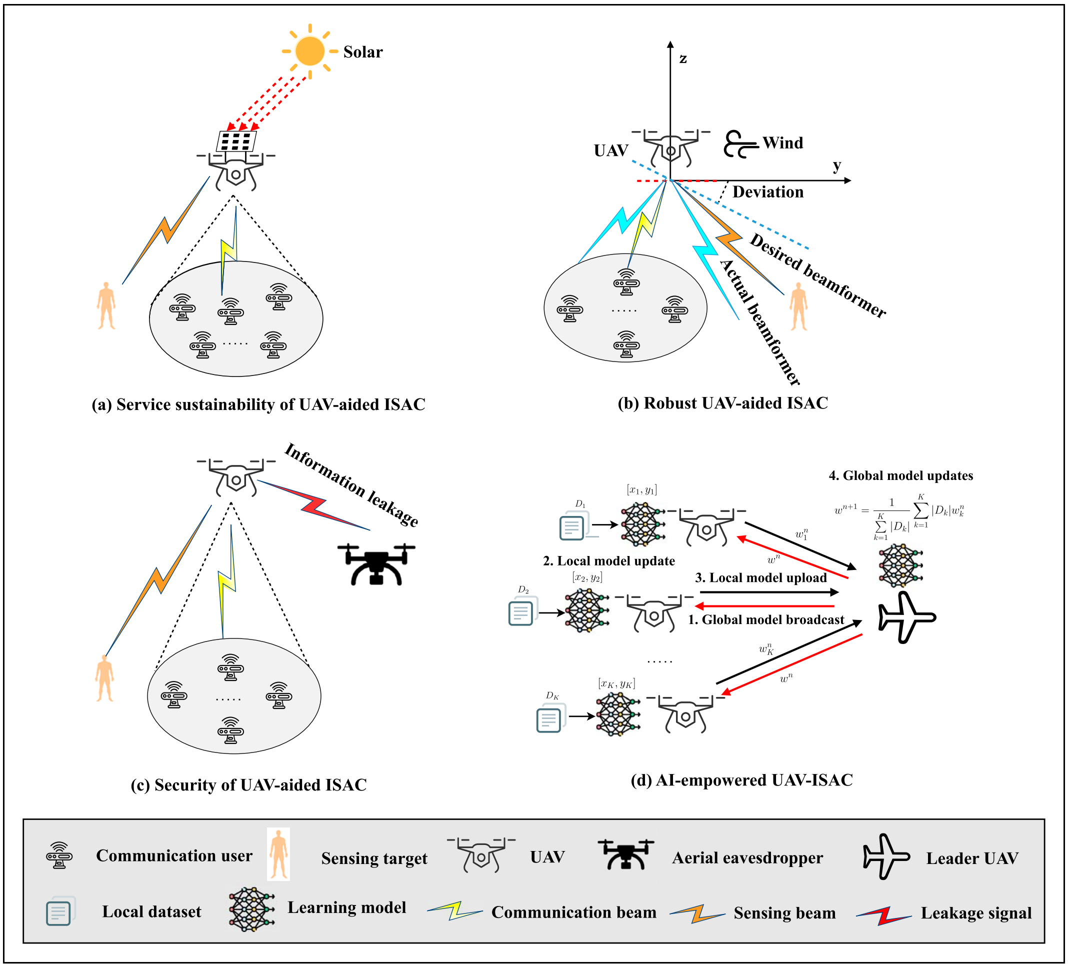


FIG. 5. Open issues of UAV-aided ISAC: (a) Service sustainability of UAV-aided ISAC, (b) Robust UAV-aided ISAC, (c) Security of UAV-aided ISAC, and (d) AI-empowered UAV-ISAC.

B. Robust UAV-Aided ISAC

Due to their small size and lightweight structure, UAVs are susceptible to horizontal and longitudinal jitters caused by wind disturbances. As shown in Fig. 5(b), such jitters will lead to the deviation of ISAC beams, and further degrade the performance of sensing and communications. Meanwhile, because of the estimation errors and limited information feedback, the channel state information (CSI) cannot be perfectly perceived in UAV-aided ISAC systems. As expected, the imperfect CSI will incur a negative impact on the sensing and communication performance, due to the beamforming gain tightly associated with accurate channel estimation. Therefore, it is essential and challenging to develop robust trajectory optimization and beamforming strategy for UAV-aided ISAC systems considering imperfect CSI and horizontal/longitudinal jitters of UAVs.

C. Security of UAV-Aided ISAC

As shown in Fig. 5(c), in UAV-aided ISAC systems, the flying altitude and open space bring the high probability to construct LoS air-ground and air-air links. Such LoS links can enhance sensing and communication performance, while simultaneously increasing the risk of information leakage. Since the conventional data-encryption methods are generally computation-intensive, they are unsuitable to be adopted in resource-constrained UAVs. In order to avoid information leakage, the physical-layer security technique is envisioned as a candidate solution in UAV-aided ISAC systems, where the artificial noise should be designed to contaminate the eavesdropping, and meanwhile ensuring the sensing/transmission performance. Meanwhile, since the eavesdroppers tend to be silent, it is difficult to obtain perfect CSI of eavesdropping links. Therefore, it is crucial to design secure sensing and communication strategies for UAV-aided ISAC considering imperfect CSI.

D. AI-Empowered UAV-ISAC

In future 6G networks, sensing and communication requirements will be highly stringent and dynamically varying across time and space. Compared with terrestrial BSs with fixed deployment positions, UAVs possess flexible mobility, offering new opportunities and challenges for meeting dynamic spatio-temporal service requirements. Leveraging its adaptability to complex environments, DRL has emerged as a promising approach for online trajectory and beamforming optimization, as it can learn optimal control policies from environmental feedback to enable autonomous ISAC operation under dynamic conditions. Nevertheless, further studies are required to improve the convergence stability, interpretability, and multi-UAV coordination in large-scale UAV-ISAC networks.

Meanwhile, federated learning (FL) provides an effective framework for enabling cooperative intelligence in multi-UAV ISAC networks, allowing multiple UAVs to collaboratively train an environment-aware learning model while preserving data privacy. As illustrated in Fig. 5(d), each UAV locally collects environment-related data such as target echo features and user location information to update its local model. The optimized parameters are then uploaded for global aggregation and subsequently redistributed to all UAVs. Through iterative model updates, UAVs can jointly adapt beamforming, trajectory design, and resource allocation strategies in dynamic environments. However, this iterative learning process imposes considerable communication and computation burdens, making training latency and energy consumption major challenges. Therefore, future research should concentrate on the joint optimization of communication and computing resources, together with adaptive model aggregation and lightweight learning architectures, to balance model training efficiency and energy consumption in FL-enhanced UAV-ISAC systems.

E. RIS- and MA-Enhanced UAV-ISAC

Benefiting from their ability to reconfigure wireless propagation environments, RISs and movable antennas (MAs) exhibit great potential for enhancing UAV-aided ISAC systems. When the direct UAV-user or UAV-target links are obstructed by obstacles, RISs can establish virtual cascaded reflection links to enable reliable information transmission and target sensing. In addition to the virtual link gain, the amplitudes and phase shifts of RIS elements can be jointly optimized to achieve fine-grained reflect beamforming, thereby mitigating co-channel interference between sensing and communication signals. Meanwhile, MAs offer additional spatial degrees of freedom for ISAC performance enhancement by dynamically adjusting antenna positions toward more favorable locations. In this context, the joint optimization of RIS configuration, UAV trajectory, MA placement, and transmission strategy becomes meaningful and challenging for improving the overall communication and sensing performance of RIS- and MA-assisted UAV-ISAC systems.

F. Quantum Communications and Sensing for Space-Air-Ground Integrated Networks

Space-air-ground integrated quantum communication networks have emerged as a promising architecture for future 6G, offering ultra-secure, low-latency, and globally connected information exchange. By linking terrestrial, aerial, and space segments through quantum links, these networks provide flexible, reconfigurable, and seamless connectivity. UAVs within this framework act as aerial quantum BSs, dynamically establishing and maintaining quantum links via adaptive trajectory control and beamforming optimization, thereby extending connectivity to remote or dynamic environments. Beyond secure communications, quantum technologies enable high-precision UAV-aided sensing by exploiting entanglement, superposition, and state estimation, achieving accurate target detection and localization even under adverse channel conditions. Therefore, integrating quantum communication and sensing into a unified framework thus supports secure, intelligent, and environment-aware UAV-enabled ISAC systems. Nonetheless, challenges related to quantum decoherence, synchronization, and resource management call for further research on resilient protocols and scalable network architectures.

VI. Conclusion

This article provided a comprehensive survey on UAV-aided ISAC. The hierarchical network framework, performance advantages, and potential applications of UAV-aided ISAC were highlighted. In addition, key technologies, including frame structure, waveform design, UAV deployment optimization, operational modes, and resource management were illustrated to promote the implementation of UAV-aided ISAC. Furthermore, a case study was presented to demonstrate the performance advantages of UAV-aided ISAC. Despite these advances, several important design challenges remain existed, such as ensuring service sustainability, robustness, and security. Besides, emerging technologies, including AI, RISs, MAs, and quantum techniques, offered promising avenues to further enhance UAV-ISAC capabilities. Since this research topic is still in its infancy, we expect that this article will provide valuable guidance for researchers to advance this technical area toward maturity.

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