UAV-Enabled Integrated Sensing and Communication: Opportunities and Challenges

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Abstract—**Unmanned aerial vehicle (UAV)-enabled integrated sensing and communication (ISAC) has attracted growing research interests towards sixth-generation (6G) wireless networks, in which UAVs are exploited as aerial wireless platforms to provide better coverage and enhanced sensing and communication (S&C) services. However, due to the UAVs' size, weight, and power (SWAP) constraints, controllable mobility, and strong line-of-sight (LoS) air-ground channels, the UAV-enabled ISAC introduces both new opportunities and challenges. This article provides an overview on UAV-enabled ISAC, by presenting various solutions for optimizing the S&C performance. In particular, we first present the UAV-enabled joint sensing and communication, and discuss the UAV maneuver control, wireless resource allocation, and interference management in the cases with single and multiple UAVs. Then, we present two application scenarios to exploit the mutual assistance between S&C, namely sensing-assisted UAV communication and communication-assisted UAV sensing. Finally, we highlight several interesting research directions to motivate future work.**

I. Introduction

Integrated sensing and communication (ISAC) has recently emerged as a candidate technology for sixth-generation (6G) wireless networks, in which wireless infrastructures and spectrum resources are reused to provide both sensing and communication (S&C) services. By leveraging advanced multiple-input and multiple-output (MIMO) and millimeter-wave (mmWave)/terahertz (THz) techniques, ISAC is expected to provide high-throughput, ultra-reliable, and low-latency wireless communications, as well as ultra-accurate and high-resolution wireless sensing in 6G [1], [2]. This thus offers new opportunities for realizing environment- and location-aware applications in smart cities, smart manufacturing, autonomous driving, etc. However, conventional terrestrial ISAC networks can only provide sensing services within a fixed and limited range, as the surrounding obstacles may block the line-of-sight (LoS) links with long-range targets and leads to seriously degraded sensing performance [3], [4].

Motivated by the success of unmanned aerial vehicle (UAV)-enabled communications [5], there is a growing interest recently in employing UAVs as cost-effective aerial

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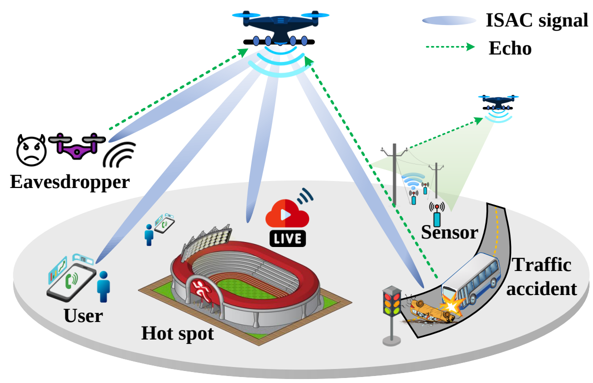

Fig. 1. The scenarios of UAV-enabled ISAC.

platforms to provide enhanced ISAC service such as traffic accident rescue, non-authorized UAV monitoring, and service enhancement in temporary hot spot areas, as shown in Fig. 1. By exploiting the UAVs' high mobility in three-dimensional (3D) space and strong air-ground LoS channels, the UAV-enabled ISAC are expected to provide better S&C coverage, flexible observation position, and enhanced S&C performance. Nonetheless, such a new aerial ISAC paradigm faces new design challenges. First, UAVs usually have stringent size, weight, and power (SWAP) constraints, which limit their communication, sensing, and endurance capabilities. Second, stronger air-ground LoS links inevitably incur more severe interference in ISAC networks [6]. Third, UAV placement/trajectory becomes new degrees-of-freedom (DoFs) to be optimized, which makes the system design more complicated. Last but not least, different from conventional UAV-enabled communications focusing on rate maximization, the UAV-enabled ISAC systems need to take into account new sensing performance metrics (such as detection probability and estimation Cramér-Rao bound) and unique sensing features (e.g., echo signal processing and clutter interference suppression) [7]. As such, how to design UAV-enabled ISAC to achieve the best S&C performance is a new and challenging problem to resolve.

With the above consideration, there is an urgent need to investigate joint S&C design in UAV-enabled ISAC systems to optimize the S&C performance by exploiting the integration gain. Specifically, proper path planning and resource allocation are urgently needed to meet the distinct S&C performance requirements and balance the performance-cost trade-off. For example, the communication service is usually continuously provided for a period determined by the data volume, while sensing tasks tend to be performed at a certain sensing frequency depending on the targets' motion state (e.g., moving speed) and the task timeliness requirement. On the other hand, always forcing sensing along with communication all the time may inevitably lead to higher energy consumption, the waste of spectrum resources, and stronger interference to communication users [8]. Moreover, multiple UAVs collaboratively providing ISAC services is an efficient solution to further enhance the S&C coverage and increase the integration gain, which, however, demands more sophisticated interference management [6].

Besides the above integration gain obtained by the joint design of S&C, mutual assistance between S&C offers another potential to achieve the coordination gain in UAV-enabled ISAC, which thus enables sensing-assisted UAV communication and communication-assisted UAV sensing. For example, UAVs equipped with (radar) sensing capabilities can design their real-time trajectories based on the sensing results and allocate communication resources while reducing the signaling overhead. In turn, wireless communications provide efficient solutions for UAVs to enhance their sensing data processing capabilities, via, e.g., sensory data offloading and over-the-air computation [9].

In view of the recent advancements above, this article aims to provide a state-of-the-art overview of UAV-enabled ISAC, by identifying its key challenges, discussing the potential solutions, and presenting interesting directions to inspire future research. Section II discusses the new design consideration of UAV-enabled joint sensing and communication designs, by focusing on single-UAV and multiple-UAV scenarios, respectively. Sections III and IV present sensing-assisted UAV communication and communication-assisted UAV sensing, respectively. Finally, Section V concludes this article by providing promising future directions related to ISAC with UAVs.

II. UAV-enabled Joint Sensing and Communication

This section presents the UAV-enabled joint sensing and communication, in which UAVs need to serve ground communication users and at the same time detect or estimate ground targets at interested sensing areas. We focus on two scenarios with single and multiple UAVs, respectively.

A. Single-UAV-Enabled ISAC

In practice, sensing and communication can be requested asynchronously over time. In this case, conventional UAV-enabled communication and sensing schemes may not work well. Therefore, for UAV-enabled joint S&C, new transmission protocols, resource allocation strategies, and UAV trajectory designs should be presented.

1) ISAC Frame Protocol Design: While communication tasks are generally implemented continuously, sensing tasks are performed periodically or aperiodically. Suppose that unified ISAC waveforms or beams are employed to sense multiple targets, for which the received sensing signal to clutter and noise ratio (SCNR) [4] or sensing beampattern [10] can be adopted as the performance metrics. During each ISAC frame, different targets may be sensed simultaneously or separately over time. Accordingly, the ISAC frame protocols can be classified into the following three categories.

- *Co-ISAC*: During each ISAC frame, all targets are sensed simultaneously at least once, where the ISAC beams need to be radiated divergently to cover all targets and users at the same time. Due to the stringent sensing requirements at all targets, in this case the UAV trajectory design is less flexible since the transmit power has to be divided over multiple directions for both S&C.
- *TDM-ISAC*: The multi-target sensing is performed in a time division multiplexing (TDM) manner along with communication, i.e., at each time instant the unified waveforms/beams only need to cover one intended target (instead of all targets in *Co-ISAC*) together with the communication users. In this case, the echo signal from other targets becomes clutters/interference for the intended target sensing. Thus, the target and users with small angular separations tend to be served together to maximize the S&C performance at the same time [2], [10].
- *Hybrid-ISAC*: This protocol is a combination of *Co-ISAC* and *TDM-ISAC*. In this design, multiple targets are grouped based on their distribution. Accordingly, *Co-ISAC* is performed within each group to improve intra-group sensing efficiency while *TDM-ISAC* is implemented among different groups to avoid inter-group interference. By properly optimizing the target grouping, this hybrid protocol is expected to outperform *Co-ISAC* and *TDM-ISAC* protocols in terms of efficiency and/or cost.

In general, the three protocol designs have their pros and cons under different scenarios, depending on various factors such as S&C quality-of-service (QoS), the locations of users/targets, and their mobility [11]. How to optimize the protocol design to enhance the S&C performance still needs further investigation.

2) Joint Resource Allocation, Waveform and Deployment/Trajectory Design: Different from the conventional terrestrial ISAC systems, in UAV-enabled ISAC systems, the optimal resource allocation and waveform design are deeply influenced by the UAV deployment/trajectory, since the angular separations between users/targets change with the UAV location. Therefore, to boost the S&C performance, the transmit beamforming and UAV trajectory need to be jointly designed so as to maximize communication performance while ensuring the sensing requirements [8]. However, finding the optimal solution to the above joint optimization problem is highly challenging, since the beamforming and UAV trajectory are closely coupled in multiple nested transcendental functions and integer optimization variables are involved such as user association and target allocation [8], [12]. To tackle this issue, in [12], a trust region-based algorithm was proposed to jointly optimize beamforming and UAV deployment/trajectory by employing the successive convex approximation (SCA) technique to transform the non-convex objective function and constraints into convex ones during each iteration. Furthermore, under the frequency requirements of sensing tasks, a two-layer penalty-based algorithm was proposed to decompose the coupled integer optimization variables for finding desired solutions [8].

To demonstrate the effectiveness of the above technique, Fig. 2 demonstrates the various UAV trajectories designs and

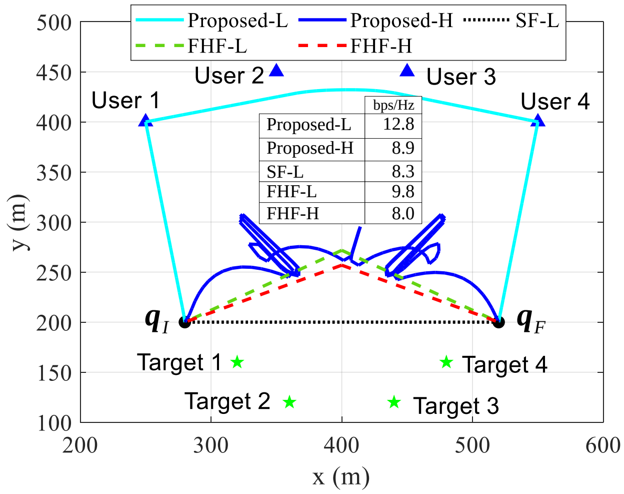

Fig. 2. Comparisons of UAV trajectory and achievable rate.

their accordingly achieved communication rates, in a scenario with 4 users and 4 targets in an area of 1 km $\times$ 1 km. The number of antennas at the UAV is 16, and the UAV's maximum horizontal flight speed is set as 30 m/s with a flight altitude of 40 m. In addition, the channel power gain at the reference distance of 1 m and the noise power at each user are set as -30 dB and -70 dBm, respectively, and the maximum transmit power is 0.1 W. In Fig. 2, two benchmarks are considered: 1) *SF*: The UAV flies from the initial location $\boldsymbol{q}_I$ to the final location $\boldsymbol{q}_F$ along the straight line at the constant speed; 2) *FHF*: The UAV flies straightly at its maximum speed from the initial location to the optimized location with the maximum achievable rate, and then flies straightly to the final location after hovering at this optimized location. Our proposed mechanism under a high (low) sensing frequency setup is referred as to Proposed-H (Proposed-L), similar for other benchmarks. It is observed that as the sensing frequency increases, the UAV's trajectory shrinks gradually from a relatively larger arc toward users to several turn-back sub-trajectories between the targets and the users. Fig. 2 also unveils a fundamental trade-off between sensing frequency and communication rate in UAV-enabled ISAC systems.

However, the complexity of the above trajectory design methods may become intractable for long flying periods, and thus how to design a low-complexity trajectory achieving satisfactory performance is a new problem of high practical interest. A possible solution for this challenge is to partition the whole period into a number of ISAC frames with limited duration. In this case, for periodic sensing tasks, we can obtain the trajectory solution in one ISAC frame, based on which the solutions in other ISAC frames can be constructed, thereby reducing the algorithm complexity [8].

B. Multi-UAV-Enabled ISAC

In single-UAV-enabled ISAC, the S&C performance may be jeopardized for geographically distributed and time-critical tasks, due to the limited capability of sensing range and communication rate in one single UAV. This thus motivates the development of effective multi-UAV collaboration mechanisms to further improve resource efficiency. Compared to the single-UAV scenario, the multi-UAV-enabled ISAC needs to deal with the severe inter-UAV interference due to the strong LoS dominant air-ground channels. Under different levels of cooperation among UAVs, we consider two scenarios with coordinated interference management and cooperative ISAC, respectively.

1) Coordinated Interference Management: In this scenario, each UAV serves its own users and targets independently, by sending uncorrelated signals. In this case, unfortunately, each UAV may pose strong interference to adjacent unassociated users/targets, thus limiting the S&C range and performance [13]. It is therefore of paramount importance to develop advanced countermeasures for managing such interference. One viable solution is exploiting UAV mobility together with beamforming design and power control for reducing inter-UAV interference. Intuitively, a number of sufficiently separated users/targets are preferred to be served simultaneously with their angular separations exceeding the angular resolution of the antenna array installed on one UAV, especially in poor scattering environments. The main reasons are that interference among UAVs caused by the side lobes of communication beams is greatly reduced and that the received signals reflected from more separated targets are distinguishable at one UAV. Furthermore, obstacles in the surrounding environment can even be utilized for interference reduction through proper deployment/trajectory design. As shown in Fig. 3, a UAV tends to stay at an optimized location that has LoS links with its associated users/targets but blocked LoS links with unassociated users/targets, thus enhancing the S&C performance while minimizing the interference. This thus leads to a multi-UAV collaboration gain.

2) Cooperative ISAC: Different from coordinated interference management, multiple UAVs are able to perform distributed radar sensing and coordinated wireless communications for deeper collaboration, thus enabling the combination of distributed MIMO radar and aerial coordinated multi-point (CoMP) transmission/reception. In this scenario, UAVs are also allowed to act as dedicated transmitters/receivers and send/receive correlated signals for collaborative S&C. From the sensing perspective, by sharing or fusing the sensing results among UAVs, larger sensing coverage, more diverse observation angles, and richer target parameters are attained from multi-UAV cooperation. Besides, the originally received signals of all UAVs can be collected and fused at a centralized UAV or on-ground base stations (BSs), and then the results are fed back to the corresponding UAVs. Furthermore, the geometric dilution of precision (GDOP), as an important factor of positional measurement precision [6], needs to be optimized to pursue large distributed MIMO gain. From the communication perspective, by exploiting the benefits of the adjustable distributed antenna of multi-UAV systems, high spectrum efficiency can be pursued with the help of the CoMP technique.

It is worth noting that NLoS links are exploitable for communication among the served users, whereas typically only LoS links are exploited for sensing and NLoS links are treated as unfavorable interference. Accordingly, the UAV at a higher

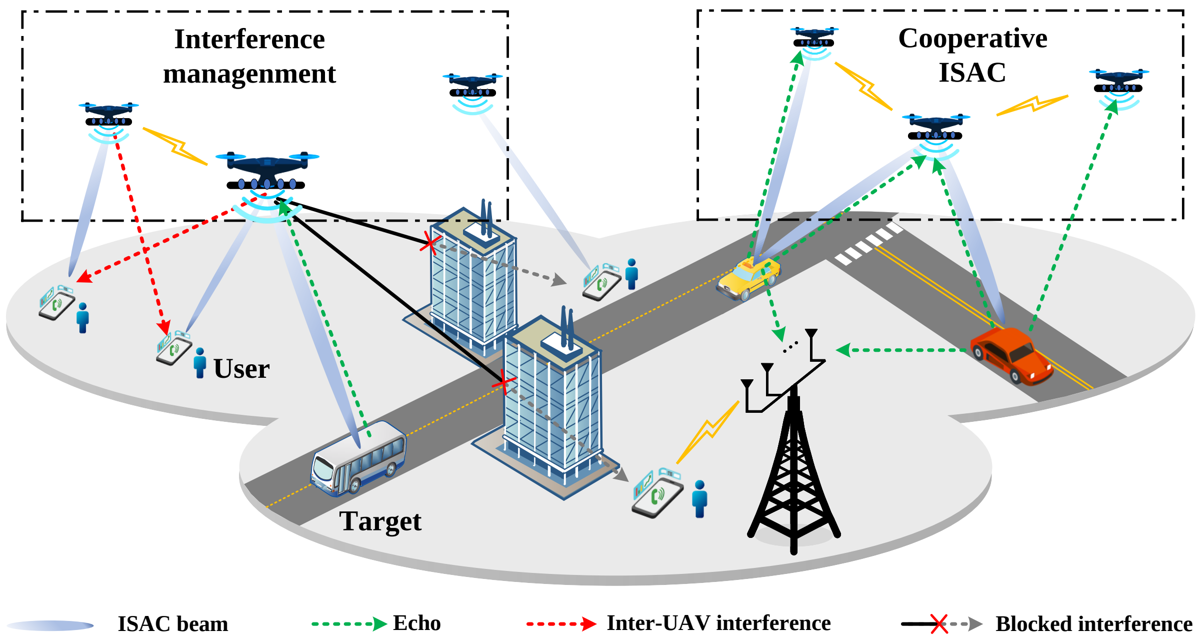

Fig. 3. A multi-UAV-enabled ISAC system for interference management and collaborative S&C.

altitude and more open environment is more likely to have strong LoS links with targets sensed by neighboring UAVs, and thus more reflected signals can be utilized for collaborative sensing; on the contrary, the multi-user communications may suffer from more potentially harmful interference and fewer DoFs of channels caused by such LoS-dominated links. Therefore, the deployment of UAVs is preferable to possess stronger LoS links to the intended targets as well as a sufficiently large number of NLoS links to communication users for achieving a high-rank MIMO channel, leading to a fundamental trade-off between S&C performance. Furthermore, the ground BSs can assist in radar signal processing and interference cancellation of communication signals in multi-UAV-enabled ISAC networks, as shown in Fig. 3. Nonetheless, such distributed multi-static ISAC system may pose several new challenges to resolve, such as high signaling overhead and strict time synchronization. Therefore, more in-depth studies are needed to find out the most suitable schemes to realize efficient and distributed multi-UAV-enabled ISAC.

III. Sensing-assisted UAV Communication

Sensing can provide an extra capability for future wireless networks to see the physical world, which in turn potentially enhances the communication performance based on their measurement results [14]. For instance, instead of relying on sending pilots to the receivers and feedback to the transmitter after channel estimation (or performing channel estimation at the BS based on the pilots sent by users), the signals reflected by the served ISAC users (collocated sensing target and communication receiver) can be directly utilized for localization and/or channel estimation. This thus helps reduce the signaling overhead and achieve performance enhancement, which gives rise to a new type of sensing gain. However, it remains unknown how to measure such sensing gain in a quantitative manner and how to fully exploit it to maximize

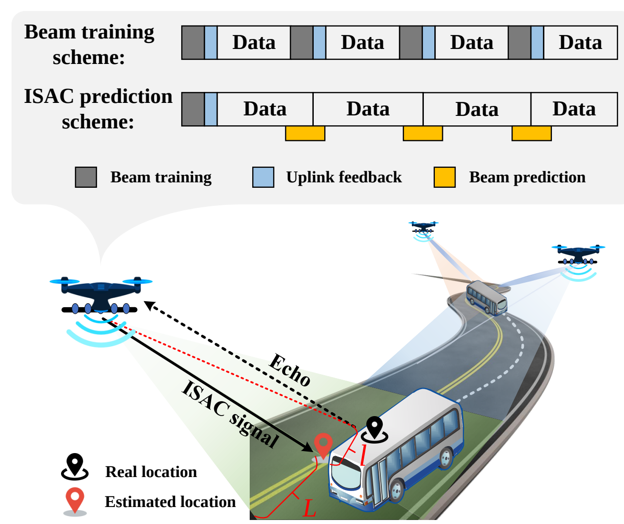

Fig. 4. Sensing-assisted UAV communication.

the communication performance by optimizing UAV trajectory and/or beamforming. To answer these questions, we particularly consider the UAV-to-ground vehicle communication scenario as shown in Fig. 4, based on which the communication performance brought by sensing gain is analyzed.

A. Sensing Gain

Instead of downlink pilots or uplink feedback, the served ground vehicle's information, e.g., location, velocity, and angle, can be extracted from the reflected ISAC signals for the use of beam tracking and beam alignment. To shed some light on the communication performance improvement gained from sensing, as illustrated in Fig. 4, the achievable rate gain achieved by the ISAC prediction scheme over the conventional beam training scheme is analyzed as follows.

First, for the ISAC prediction scheme, the estimated vehicle location error may lead to beam misalignment, and the corresponding misalignment effect on the received communication signal-to-interference-noise-ratio (SINR) of the echoes can be modeled based on the location error l [15], denoted by $\beta_p = C_1 e^{-2l^2/L^2}$, where C_1 is a constant and L represents the equivalent beamwidths, as illustrated in Fig. 4. Then, the corresponding achievable rate is $R_p = \log_2(1+\beta_p\gamma_0)$, where γ_0 is the optimal SINR with perfect beam alignment. For comparison, in the conventional beam training mechanism, the achievable rate of the served user is $R_t = (1-\alpha)\log_2(1+\beta_t\gamma_0)$, where β_t denotes the SINR loss caused by angle quantization and beam training error, and α represents the overhead of downlink pilots. Accordingly, the communication performance improvement gained from sensing, namely sensing gain, is characterized by $R_p - R_t$.

Based on the above discussion, the more (less) accurate the target estimation (channel estimation), the greater the sensing gain that can be achieved. Under the LoS-dominated channel, the location estimation error l is generally related to the fourth power of the link distance between the UAV and the ground vehicle due to the round-trip path loss of the reflected signals, while the SINR loss of beam training scheme is related to the received signal power at the ground vehicle. Accordingly, the achievable rate gain achieved by sensing-assisted communication may decrease as the link distance increases. This is illustrated in Fig. 5, where the end-to-end spectrum efficiencies for the beam training scheme and the ISAC prediction scheme are plotted for the setup that the ground vehicle moves along x-axis and the UAV is hovering with $x = 700$ m. It is observed from Fig. 5 that a higher sensing gain is provided when the ground vehicle is closer to the UAV, and the performance of the ISAC prediction scheme decreases if the echo signal power becomes weak. As a result, exploiting the UAV's mobility to shorten the link distance not only reduces the large-scale path loss but also strengthens the corresponding performance improvement gained from sensing.

For the general multi-UAV scenarios, collaborative sensing potentially leads to significant communication performance improvement but needs more complicated cooperation schemes. Particularly, how to realize efficient and reliable sensing data exchange and fusion among multiple UAVs for high-quality and seamless-coverage communication is an open problem, which deserves further investigation.

B. Sensing-assisted Beam Tracking

How to achieve precise target tracking and high beamforming gain for communication remains an open problem that needs further investigation. Specifically, for a far-apart user that can be deemed to be a point-like object, the sensing/radar beam should be designed as narrow as possible to accurately point towards the receive antennas, thereby providing both high beamforming gain for communication and excellent angular resolution for sensing. For a nearby user, it can no longer be viewed as a point but rather as an extended object, since the communication receiver may be beyond the beam coverage even though the user is accurately located. One possible approach to tackle this practical challenge is to employ a dynamic waveform scheme for adjusting the width and center of ISAC beams in real time according to the relative position of the receive antenna with respect to the estimated contour of the object. For example, in the S&C stage, the beamwidth is designed to cover the object for guaranteeing sensing accuracy, while in the communication-only stage, a thinner beam can be adopted to align its receive antenna. Besides, for users with high mobility, UAVs tend to use wide beams to provide reliable and effective target tracking at the proper distance to the target, while improving the communication performance by adopting narrow beams at a closer distance to the target. This leads to a fundamental trade-off between communication throughput and sensing reliability for joint beamwidth and UAV trajectory design. Therefore, how to provide reliable beam tracking and enhanced communication by exploiting UAV's mobility and beamwidth design is a new and practically important problem.

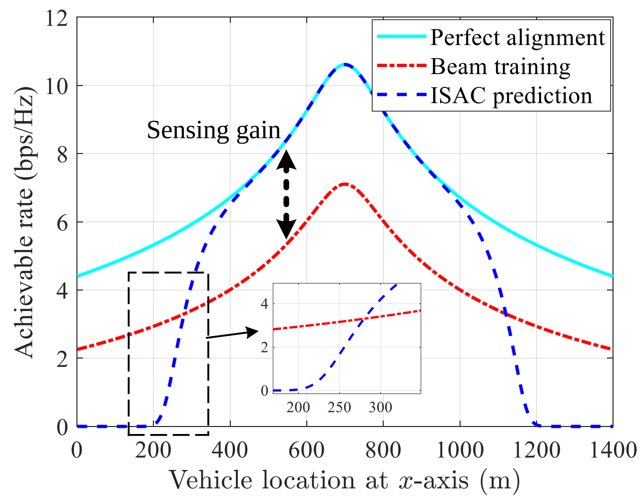

Fig. 5. Sensing gain achieved by ISAC prediction scheme over beam training scheme.

C. Sensing-assisted Predictive Resource Allocation

Although multi-UAV-enabled ISAC is promising for performance and coverage extension, it faces several practical challenges in resource allocation and user scheduling at the network level, such as dynamic load balance and seamless coverage. For example, in multi-UAV networks, some UAVs may suffer from heavy S&C traffic loads while others only have light loads, due to the uneven distribution and mobility of users. This thus seriously degrades the service time and quality due to the limited energy and resources of each UAV. One possible solution is to allow the UAVs to actively/passively monitor the served users' state (e.g., position and velocity) by analyzing the reflected signals from users, and then predict their trajectories based on the measured information. Then, these results can be further exploited to optimize the network resource allocation and user scheduling, thus achieving high-quality service by preparing resources and communication data for the corresponding users in advance. In general, there are still open and challenging issues for seamless coverage and connectivity in multi-UAV networks, especially in urban environments with many potential obstructions. Thus, how to jointly design dynamic UAV deployment and resource allocation to provide seamless service is also crucial.

IV. Communication-assisted UAV Sensing

Besides sensing-assisted UAV communication, the communication functionality can also assist sensing in return, to enhance the robustness, efficiency, and accuracy of sensing.

A. Data Offloading

As the sensing results are generally demanded in subsequent processes, one challenge for UAVs to perform sensing tasks in practice lies in their limited computation ability and the high timeliness requirements of data processing. For example, processing all the received echoes locally at the UAV may be too time-consuming to meet the latency requirements of delay-sensitive ISAC missions, such as target tracking. To tackle this problem, one viable solution is to offload some computationally-intensive sensing tasks (e.g., raw data or processed data) to the nearby edge servers (e.g., on the ground BSs or a central UAV with powerful computing capabilities), as shown in Fig. 6. By judiciously selecting the computing nodes (e.g., those with strong LoS links to the UAV) and scheduling multi-dimensional resources (e.g., communication resource allocation and offloading ratio optimization), a more efficient ISAC service ensuring the timeliness of perception results can be provided. However, how to balance the energy consumption and transmission/processing latency deserves further study. Moreover, due to the potentially large amount of sensory data and limited link capacity, advanced compression methods may be applied to pre-process the sensing results and reduce the transmission burden. Alternatively, multiple UAVs may form multi-hop links for collaboratively relaying and offloading the sensing tasks.

B. Information Sharing and Fusion

Considering the limited sensing range and performance of a single UAV, another solution to improve the sensing performance is to allow multiple UAVs to share and integrate their information for joint processing. For example, the individually estimated information about users' position and velocity is exchanged among UAVs, and thus a more efficient sensing mission assignment can be provided in the next ISAC frame. By sharing the user's moving direction and the changes of the surrounding environment, a multi-UAV system with maneuver control is envisioned to collaboratively provide seamless coverage and tracking. On the other hand, by information sharing, the resource wasted by repetitive target detection and excessive target searching is avoided. Furthermore, a UAV or a ground BS can serve as a data center for the collection and fusion of sensing results, thus improving the sensing accuracy and obtaining richer target information. However, information sharing/exchanging also brings transmission latency and the consumption of communication resources. Hence, how to design a low-cost and high-efficient data sharing/fusion strategy to improve network sensing performance is an open

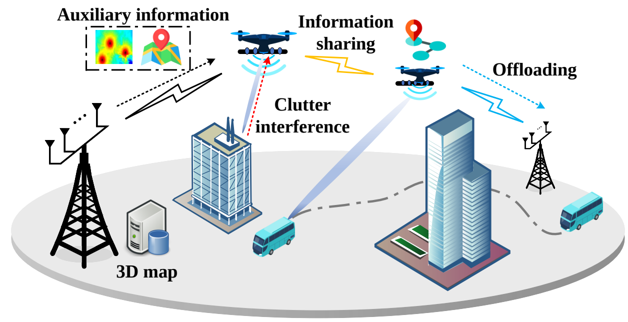

Fig. 6. Communication-assisted UAV sensing.

and challenging issue. Moreover, considering the limitation of communication rates, it is practically difficult to meet the timeliness requirements of sensing information, especially for wireless data aggregation in swarm UAV scenarios. A promising approach to reducing data fusion time is to apply the over-the-air computation technique [9], which exploits the waveform superposition property of a wireless channel to realize over-the-air aggregation of data simultaneously transmitted by multiple UAVs, without the need for separate data demodulation and fusion processes.

C. 3D Map Assistance

One challenging issue related to UAV sensing arises from undesired environmental obstacles, which could either block LoS sensing links or cause clutter interference. For example, when a UAV flies to an unknown area to perform ISAC missions, the UAV-ground channels may be occasionally blocked by high-rise buildings in urban areas, which degrades the practical S&C performance. To overcome the above issue, one possible solution is employing the environment map constructed based on historical measurements. For example, the nearby BSs or edge servers transmit the stored 3D map of the surrounding environment to the UAV, and based on this map, the link states between the UAV and targets can be predicted. In turn, the map can be further updated based on the current sensing results. However, only relying on map information may result in poor ability to deal with the dynamics of the environment. To tackle this problem, one viable method is to combine the offline LoS modeling and online sensing information, thus more accurately judging whether there exists a LoS link between the UAV and a given target location. Hence, the UAV can design its real-time trajectory to provide enhanced and reliable ISAC services by maintaining the served users within its LoS-link area. Furthermore, it is also possible to extract auxiliary information for sensing based on the 3D environment map, such as the features of the explored/served areas and the potential clutter. With such information, the UAV is able to obtain awareness of the environment around it and reduce/cancel clutter interference for facilitating target sensing, as shown in Fig. 6.

V. Conclusions and Future Works

In this article, we have discussed UAV-enabled ISAC to achieve integration gain and mutual assistance. New design considerations and key challenges are highlighted for UAV-enabled ISAC networks. Notably, some representative applications of coordination gain of ISAC, i.e., sensing-assisted UAV communication and communication-assisted UAV sensing, are presented to demonstrate that S&C are complementary. Furthermore, the case study verifies the proposed methods. As UAV-enabled ISAC remains largely unexplored, it is hoped that this paper would provide a useful guide for future research on them. In particular, some open issues related to ISAC with UAVs are discussed as follows.

A. ISAC for UAVs

ISAC networks can also be utilized to monitor and manage the network-connected UAVs, especially for UAVs with low altitudes. For network-connected UAVs, the ISAC signals can be utilized for tracking UAVs and thus enhance the communication performance through efficient beam prediction. As such, by exploiting the UAV's reflected signals, a more reliable cellular connection can be achieved by proper resource allocation and trajectory design. However, the strong UAV-ground LoS links inevitably increase the interference to the terrestrial users/BSs. This motivates new techniques for cooperative interference management and cancellation for heterogeneous ISAC networks.

B. IRS-assisted UAV-enabled ISAC

Intelligent reflecting surface (IRS) is a promising technology to reconfigurable wireless channels by exploiting the smart reflection of massive low-cost reflecting elements. With the exploitation of IRS, a virtual LoS link between the UAV and the blocked users can be established to enlarge UAV's coverage. This in turn provides higher flexibility for the UAV deployment/trajectory design to achieve better S&C performance. Thus, both IRS and UAV can boost S&C performance by proactively altering the wireless communication channels via joint phase shift and maneuver design. Accordingly, a more flexible trade-off is provided for IRS-assisted UAV-enabled ISAC system, while the joint system design becomes more complex.

C. Secure UAV ISAC

The UAV-enabled ISAC system brings a higher risk of eavesdropping and jamming attacks arising from the LoS-dominated air-ground channels. On the other hand, unauthorized malicious UAVs also pose a new security threat to ground ISAC networks. As such, how to effectively safeguard the legitimate S&C users (e.g., prevent target location and user information from being eavesdropped) and how to efficiently protect the S&C services (e.g., accurate sensing and reliable communication) against the malicious attacks are new and challenging problems to resolve. Combing information signals with artificial noise is a promising solution for target/eavesdropper tracking, but providing secured ISAC services is still complicated due to the difficulty in obtaining the locations and channels of eavesdroppers.

D. UAV ISAC Meets Artificial Intelligence

While this article focused on the optimization-based design approaches for UAV-enabled ISAC, these design approaches may not work well in practical scenarios when the wireless channels fluctuate significantly and users move dynamically over space. The artificial intelligence (AI)-based approaches are promising tools for addressing the dynamics while avoiding the time-aggressive iterations of traditional optimization algorithms. By collecting information about the environment states and training properly, the future network states are predicted, which allows UAVs to adaptively adjust their actions in an online manner. In turn, ISAC can provide training data for new AI-enabled applications via wireless network sensing. To properly train AI models by using ISAC data at distributed UAVs while preserving their privacy, the federated learning (FL) can be an efficient solution, where each participating UAV-BS updates its local AI model based on its own local ISAC data, and then sends the updated parameters to a central server for global AI model update. How to deploy the training algorithm together with the ISAC process is an interesting problem.

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