

Integrated Radar Sensing, Communication and Computation UAV Networks: A Survey

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Abstract—This paper provides a comprehensive survey of works that leverage Integrated Sensing, Communication (ISAC) or/and Computation (ISACC) in networks with one or more Unmanned Aerial Vehicle(s) (UAVs). In these works, UAVs use their radio as a radar when communicating with users to collect information such as the range and velocity of targets. Example targets include obstacles, aerial/ground eavesdroppers or jammers, or/and users. Further, sensed data collected by UAVs may require computation, where data is either computed locally by a UAV or offloaded to another UAV or a ground base station. We categorize prior works based on whether they have (i) a single, or (ii) multiple UAVs. Within each category, we further divide works according to whether they have a single or multiple users or/and targets. Further, we outline their research aim, performance metrics, optimization problem and constraints. Lastly, we present a number of possible research directions.

Index Terms—Perception, Cooperative Sensing, Resource Allocation, Mobile Vehicles, Drones, Cramér-Rao Lower Bound.

I. INTRODUCTION

To date, there has been extensive research on the use of Unmanned Aerial Vehicles (UAVs) or drones to aid sensing and communications in future wireless systems [1], [2], and provide various services such as computation [3], Drones as a Service (DaaS) [4], [5] or/and remote sensing [6] to name a few; all of which are indispensable in the vision of low altitude economy [7]. This is not surprising as UAVs have the following characteristics: (i) *maneuverability*, which allows them to be placed in positions that ensure line-of-sight (LoS) to a ground node/target or/and other UAVs; this is particularly important given that sensing relies on LoS. Further, UAVs can be used to alleviate the double path loss of radar/sensing signals. Moreover, UAVs can be used to provide different angles/perspectives or sensing modalities of a target [8]. This is particularly important if there are multiple targets located at the same location. In this respect, UAVs can alter their position to gain better resolution of targets. They can also be used for localization [9], or by applications that require contextual information, e.g., augmented reality [10] or during a disaster [11]. (ii) *accessibility*, where they can be

deployed to cover hostile terrains/environments, see [12], (iii) *versatility*, where they can be equipped with various sensors, processors, or/and reconfigured to transport various payloads in logistic applications [13]. Further, they can form an aerial communication backbone [14], [15], [16], where UAVs run various services, e.g., inference, required by users [5], and (iv) *cost advantage*, where they provide a cost effective solution as compared to conventional methods for data collection from devices in remote and harsh areas, inspection of critical infrastructure such as power lines [17], or last mile delivery of parcels [18].

UAVs are equipped with various sensors such as cameras, accelerometer, and Inertial Measurement Unit (IMU) to name a few. These sensors allow a UAV to ascertain its attitude, to navigate, and to collect environmental conditions; e.g., robots using Simultaneous Localization and Mapping (SLAM) to map and ascertain their location [19]. Of interest in this paper are UAVs that track/monitor one or more targets such as ground or/and aerial vehicles, where they collect data such as range/distance, velocity, orientation, shape, materials, or/and size to name a few. Such data helps a UAV avoids obstacles during flight [20], [21], where an obstacle could be a building or another UAV [7]. Advantageously, such data is beneficial to wireless communications as well, especially in millimeter wave communication systems as signals are affected by obstacles. As we will discuss later, the said data helps a transmitter shapes its beam to improve communication rates, avoid the costly process of sending pilot symbols to estimate a channel as well as avoid an eavesdropper.

Recently, there has been significant interests in using the same communication hardware and software on a node to facilitate sensing, see Section I-A for more details. As we will see later, the main research goal of Integrated Sensing and Communication (ISAC) or Joint Communications and Radar (JCR) works is to maximize spectrum, hardware and information efficiency; i.e., it enables sharing of resources such as energy and bandwidth. In general, these works aim to reuse existing spectrum to maximize both communication and sensing rates; the spectrum under consideration includes those used by communication and radar systems. To do so, they leverage the Radio Frequency (RF) chain(s) on a node to achieve both communication and sensing; this is also called *integration gain*. Another goal is to maximize *beamforming gain*, where a node beamforms to simultaneously carry data and detect target(s). Here, a node may be a transmitter in an existing communication system or a radar system [22], [23].

There are a number of factors that drive ISAC interests; see Figure 1 *First*, next-generation communication systems

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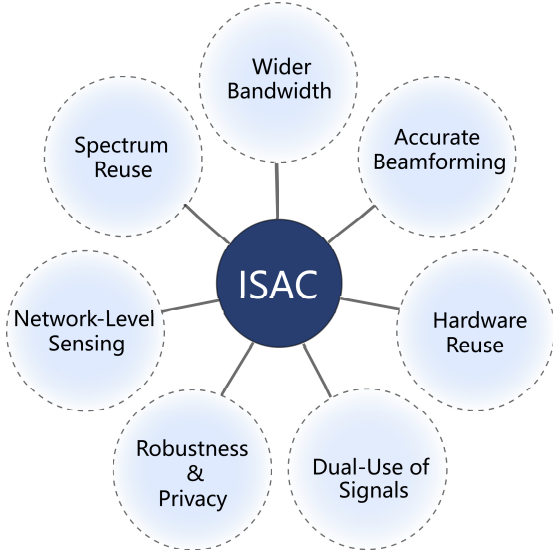


Fig. 1. Factors that drive the adoption of ISAC.

are adopting higher frequencies, have wider bandwidth, and multiple antenna elements. Hence, these systems, which operate in the gigahertz [24] and terahertz [25] frequency bands, help improve spatial resolution that allows multiple targets to be detected due to their wide bandwidth and ability to focus energy at specific target(s). Further, the higher frequencies or shorter wavelengths help facilitate the detection of targets, especially other UAVs. Apart from that, sensing performance will benefit from the adoption of massive Multi-Input Multi-Output (MIMO) technologies in future communication systems. Specifically, sharp non-interfering beams can be formed for communication and sensing simultaneously. Moreover, they lead to better angle-of-arrival estimations. *Second*, sensing aids communications [26]. In this respect, millimeter wave (mmWave) communications will benefit significantly. Specifically, it can be used to address the beam tracking problem when communicating with mobile receivers [27], [28], [29]. Apart from that, a transmitter can also glean channel information, which helps reduce channel estimation overhead [28], [30], [31]. Moreover, echoes from a target can be used to determine interference intensity at a receiver. Apart from that, mmWave systems that use pencil-beam (narrow beams), e.g., [32], have fewer echoes as compared to systems that operate in lower frequencies due to less scattering [33]. This in turn helps improve sensing performance.

Third, ISAC helps reduce the weight of UAVs as they do not require separate hardware or antennas to monitor/track target(s) or operate in a swarm [20]. This also reduces their radar cross section or detection probability. *Fourth*, it helps a UAV utilizes its energy more efficiently as each Joule of energy is used for both communications and sensing of target(s). This becomes particularly important for energy limited systems such as a UAV. Moreover, nodes do not require separate hardware, components or a dedicated node for sensing, all of which incur additional power to operate. *Fifth*, RF signals are robust as compared to other sensors based on acoustic, vision or light. This means ISAC allows UAVs to operate

at night and in different weather conditions. In addition, the use of RF signals invokes less privacy issues as compared to cameras [34]. Apart from that, ISAC affords UAVs additional sensory input to identify obstacles, a rogue UAV [35] or to acquire features required by machine learning models [36].

Sixth, future communication networks will be ultra-dense, comprising of a high number of base stations, users and devices. This in turn leads to so-called Internet of radar [37]; this is also called network sensing [26] or perceptive mobile networks [38], [39]. Advantageously, they help improve resolution, accuracy and sensing over a wide area, which encompasses indoor and outdoor environments. Moreover, as noted in [33], they can be used to detect rogue UAVs operating in suburban areas. In general, as noted in [26], ISAC allows nodes in communication systems to carry out device-free sensing, especially of so-called passive targets that do not have sensing/localization or communication capabilities.

Seventh, a key concern in next generation wireless systems is the lack of spectrum to meet higher traffic demands. This concern spurs research into communication technologies that exploit radar spectrum, especially those occupied by conventional systems operating below 10 Gigahertz (GHz) [33], [40], and also to use these systems or radar signals to covertly carry information [41]. However, a key issue is that the resulting data rate is low. This motivates the use of millimeter systems to achieve high data rates and sensing resolution. Lastly, as per [42], reusing existing licensed and unlicensed spectrum means there is less or no regulatory requirements that would otherwise hinder deployment of ISAC systems.

A. Prior ISAC Surveys

Given the aforementioned factors and motivations, it is not surprising that ISAC has received considerable attention. This is also evidenced by the many articles that have provided a tutorial of radar concepts, and a diverse set of potential ISAC applications. Many articles have also discussed signal processing and theoretical bounds of ISAC systems. The interested reader is referred to the articles in Table I. Briefly, articles such as [28], [34], [38], [42], [43], [44], [45], [46], [47], [48], [49] have provided an extensive list of motivations, and potential applications of ISAC; these references have the letter 'I' in the *Type* column of Table I. A historical account of technologies that led to ISAC can be found in [22]. In addition, articles [50], [51] and [52], [53] respectively analyzed how ISAC can be realized using standards such as IEEE 802.11, and current and future cellular networks. Most articles propose interesting research directions such as the incorporation of massive MIMO, terahertz communications [50] and Reconfigurable Intelligent Surfaces (RIS) to name a few. Of interest are future directions involving network sensing whereby multiple nodes, e.g., base stations, cooperate to help sense target(s), see [37], [23] for further details.

We emphasize that all the aforementioned articles are not focused on UAVs where they only noted how ISAC will benefit UAVs as a side note. In this respect, to date, only references [36] and [54] have provided a more in-depth discussion of ISAC-capable UAVs. They outline why and how UAVs will

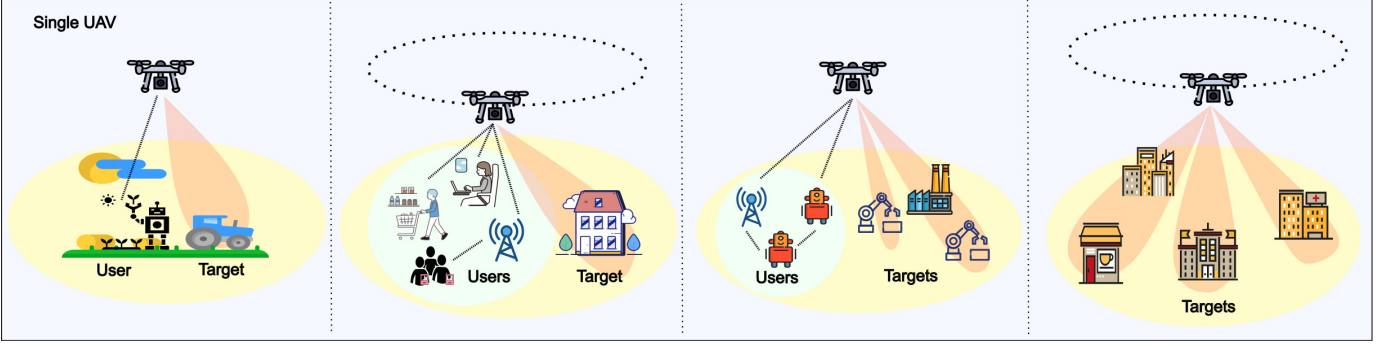


Fig. 2. Different scenarios discussed in Section II with a single UAV, where a UAV is required to beamform to one or more users or/and targets. We use a line to denote a communication link and orange beams denote sensing; in practice, a UAV beamforms to both user(s) and/or target(s).

benefit from ISAC technologies, and issues that may arise when UAVs use ISAC. These issues include interference, trajectory control, impact of wind and energy to name a few. Further, in [54], the authors consider frame formats that allow for varying sensing frequency and communications, and issues in sensing-assisted communication as well as communication-assisted sensing. These works, however, have only provided an *overview* of these issues.

B. Contributions

In contrast to prior surveys, we provide a comprehensive survey of works involving a single and multiple ISAC-capable UAVs that are tasked with tracking target(s) and concurrently communicate with user(s). In addition, it also covers works that involve computation of sensed data, i.e., ISAC plus Computation (ISACC), which involves processing of radar signals or/and tasks from users. As compared to the survey articles in Table I, this paper makes the following contributions:

- It is the first comprehensive survey to focus on networks with ISAC or ISACC capable UAVs. It covers works that use these UAVs to sense target(s) and communicate with user(s) or/and base stations, or compute data locally.
- It shows how prior works can be categorized based on single or multiple UAVs. Within each category, we further divide them based on the number of users and targets. We also discuss works that only consider sensing/tracking of targets and computation of sensed data.
- It provides qualitative comparisons of the network components and key resources optimized by prior works with a single or multi-UAVs. It identifies common components, variables and performance metrics adopted in the optimization models of prior works.
- It provides a set of novel research directions ranging from link scheduling or channel access methods, sensing as a service using UAVs, which includes computations by UAVs, consideration for environmental factors such as wind, and upcoming wireless technologies.

C. Scope

This paper focuses only on works where UAVs use their radio(s) for (i) communications with aerial or ground nodes,

and (ii) sensing of static/mobile aerial/ground targets. It excludes works that use other sensor types, e.g., a camera [59]. In addition, works that aim to use UAVs as anchor nodes for localizing node(s) are out of scope. Also, this paper does not cover works whereby ground base stations use ISAC to localize UAVs; see [60] for a recent survey. Apart from that, we also note that many works have considered using UAVs for localization, e.g., [61], where one or more UAVs act as anchors at different hovering points that are then used by ground devices to determine position. These works, however, do not involve radar. We also note that our focus is on prior works that involve resource allocation, where they leverage optimization theory or/and reinforcement learning to determine the optimal resources, e.g., transmit power, that optimizes communication and/or sensing performance.

To date, there are many surveys on the application of UAV(s) in various settings. Examples include data collection, e.g., [62], drone scheduling, e.g., [63], and creating a multi-UAVs network to track aerial or/and nodes, e.g., [64]. They, however, do not consider ISAC or ISACC.

D. Road Ahead

The main idea is to group prior works based on their network/system setup before delving into their specific aim and problem. Figure 3 provides an overview of the sections to follow, where we divide works based on the number of UAVs as well as the number of users and targets, namely (i) single user and single target (SUST), (ii) multiple users and a single target (MUST), (iii) multiple users and targets (MUMT), or (iv) targets only. Further, as we will see later, within each category, we can further divide prior works based on whether they aim to optimize communication, sensing or both. In addition, for each aim, we further group them based on their performance metric, e.g., sum-rate and secrecy rate for communication, and target detection probability and beamforming gain for sensing.

Note that in our discussions, the term *user* refers only to a node that transmits or receives data from a UAV. Conversely, the term *target* is the object being sensed by a UAV, where an object could be another UAV, user or an obstacle; i.e., a target is usually a passive target meaning it does not transmit/receive. A user is considered an active target, where a base station or

TABLE I

A COMPARISON OF PRIOR WORKS. THE TYPES OF ARTICLES INCLUDE INTRODUCTORY OR VISION (I), SURVEY (S) OF SPECIFIC TOPICS, E.G., SIGNAL PROCESSING, OR MIXED (M), WHICH PROVIDES SOME INTRODUCTION FOLLOWED BY A SOLUTION TO A SPECIFIC PROBLEM. THERE IS A TICK IN A COLUMN ONLY IF AN ARTICLE PROVIDES AN EXTENSIVE REVIEW OF THE COLUMN'S TOPIC. IN THE "UAV(S)" COLUMN, THE PERCENTAGE IN WHICH A CIRCLE IS FILLED DENOTES THE COVERAGE LEVEL OF A TOPIC.

Work	Year	Type	Basic Concepts	Survey Applications	Waveform Design	Resource Allocation	Signal Processing	Network Sensing	UAV(s)
[40]	2016	I	✓	✗	✓	✗	✗	✗	○
[55]	2019	I	✓	✗	✓	✗	✗	✗	○
[50]	2019	I	✗	✗	✗	✓	✗	✓	○
[37]	2020	I	✗	✓	✗	✗	✗	✓	○
[43]	2020	S	✓	✓	✓	✓	✗	✓	○
[33]	2020	M	✗	✓	✓	✓	✓	✗	○
[51]	2021	I	✗	✗	✓	✓	✓	✓	○
[52]	2021	I	✓	✓	✓	✗	✗	✓	○
[28]	2021	M	✓	✗	✓	✓	✗	✗	○
[44]	2021	I	✓	✓	✓	✓	✗	✗	○
[38]	2021	I	✗	✓	✓	✓	✗	✓	○
[46]	2021	S	✓	✗	✓	✗	✓	✗	○
[47]	2021	I	✓	✓	✓	✗	✗	✗	○
[42]	2021	I	✗	✓	✓	✓	✗	✓	○
[48]	2021	I	✗	✓	✓	✗	✗	✗	○
[45]	2022	I	✓	✗	✗	✓	✗	✓	○
[56]	2022	S	✗	✗	✗	✗	✗	✓	○
[53]	2022	S	✓	✓	✓	✓	✓	✓	○
[22]	2023	S	✓	✗	✓	✗	✓	✗	○
[36]	2023	I	✗	✓	✗	✗	✗	✓	○
[23]	2024	S	✓	✗	✓	✓	✓	✓	○
[57]	2024	S	✗	✗	✓	✓	✓	✓	○
[54]	2024	I	✗	✗	✗	✓	✗	✓	○
[58]	2024	S	✗	✗	✗	✓	✓	✓	○

UAV may localize and track a user's location. Further, the term *sum-rate* refers to the total data rate received by users. For targets, we write *sensing rate* or *mutual information rate*.

II. SINGLE UAV

Figure 2 provides an overview of networks considered in prior works with a single UAV that has to enable communications to/from one or more users, and at the same time sense one or more targets. There is also a scenario whereby the UAV collects sensed targets only. In general, prior works have the following features:

- They involve UAV trajectory optimization, where a key decision is the determining the coordinate of the UAV over time subject.
- The UAV usually is equipped with a Uniform Linear Array (ULA) or Uniform Planar Array (UPA)¹, which allows it to focus its transmission on target(s), or/and users (or a base station). Hence, optimizing its beamforming vector or precoding matrix is critical.
- A single cell or area, where a UAV only has to consider targets and users within a given area without considering interference to/from other cells or nearby networks.
- Users and targets are usually static, and they are distinct entities, meaning a transmitter does not usually aim to track a receiver/target. In addition, receivers are located on the ground, and have a fixed location.

¹We refer the reader to works such as [65] for details on how ULA/UPA can be achieved on a UAV.

- Targets have known or unknown mobility. The unknown target location case is usually addressed using a Kalman filter or a reinforcement learning approach.
- Performance metrics of interest include sum-rate for users, and Cramér-Rao Lower Bound (CRLB), beamforming gain, beam pattern error, target detection probability, and radar mutual information rate. Common metrics are highlighted in Table II. A less common sensing metric is the accumulated sensing energy over a given time interval, see [66], [67], or across all targets [68].

A. Single-User Single-Target (SUST)

A UAV can act as a relay, where it helps forward messages to/from a user that may reside outside the range of a base station [16], [69]. To this end, the authors of [70] use reinforcement learning to learn a policy that places a UAV in 3D space in order to serve a mobile user; i.e., the base station adapts the position of the UAV with respect to the mobile user. It also optimizes the duration of pilot signals that are used by a base station to estimate the position of the UAV; i.e., the base station is a monostatic radar. The optimal policy maximizes a weighting between communication capacity to the said user and sensing performance of the user, as measured using CRLB.

A number of works have considered a UAV that communicates and localizes a user simultaneously. Examples include [71], [72], where a UAV flies over multiple hovering points and measures its distance to a user. Here, the problem at hand is to determine these hovering points as well as the

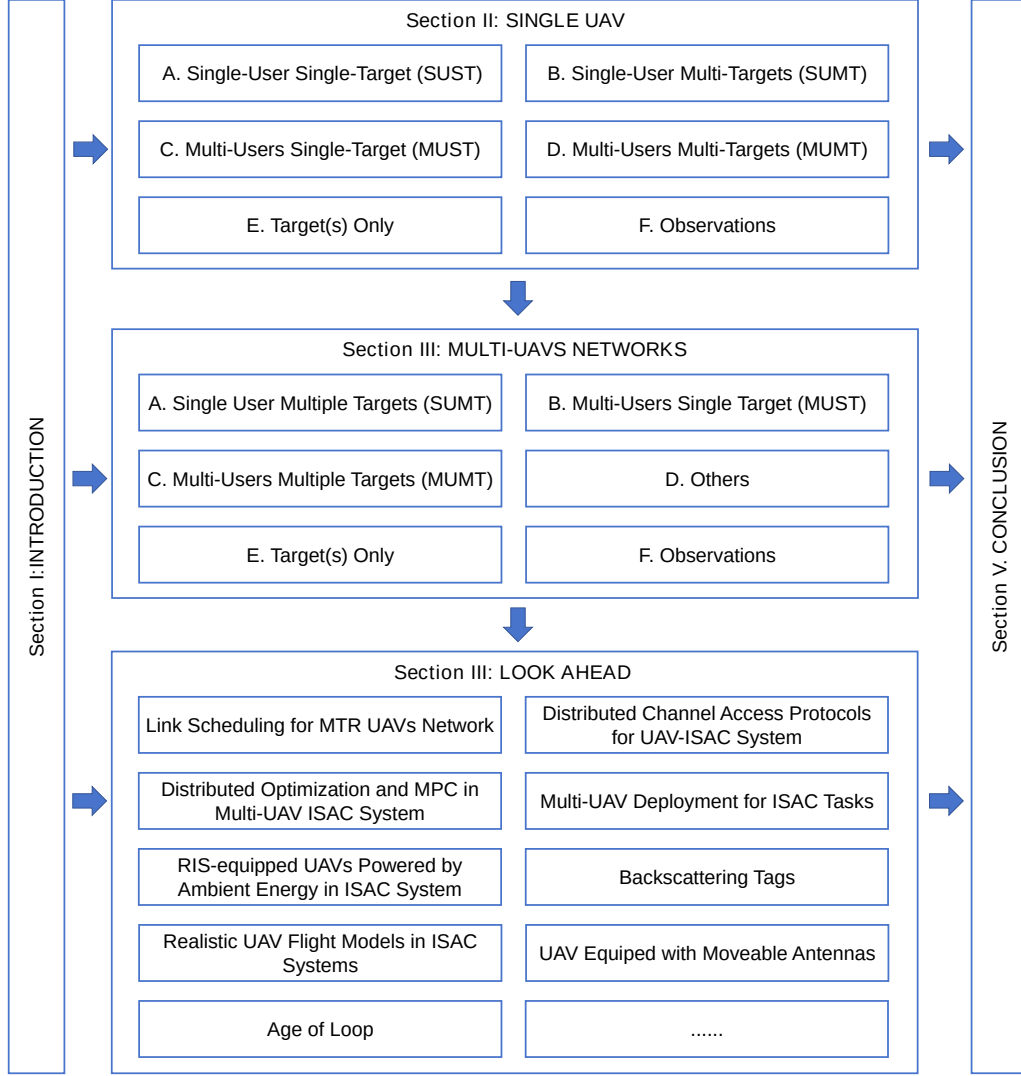


Fig. 3. The organizational structure of this survey.

TABLE II
COMMON COMMUNICATION AND SENSING PERFORMANCE METRICS.

<i>Metric</i>	<i>Indicator</i>	<i>Comments</i>
Communication	Sum rate	The total data rate across all users, either over one or multiple time slots.
	Max min rate	This metric ensures fairness, where the goal is to maximize the user with the smallest data rate.
Sensing	Cramér-Rao Lower Bound	This ensures the lowest estimation error of a target.
	Detection probability	This quantifies the probability of finding a target.
	Beam pattern gain	This measures the amount of transmit signal power at a target.
	Beam pattern error	This quantifies the error between the beam formed by a UAV and a reference beam.

UAV's velocity that jointly minimize the CRLB of user's estimated location and maximize the communication rate of the user. In a different work, reference [73] considers a UAV that is communicating with a mobile user/target that moves along a horizontal path. It aims to track the target's relative position and velocity. To do this, it uses an extended Kalman Filter to track the user/target's elevation angle, time delay and Doppler shift. The optimization problem is to determine the UAV's trajectory that minimizes estimation errors subject to a minimum data rate at the target/receiver.

The work in [74] considers a hovering UAV that is communicating with a slowly moving user. Further, the UAV is perturbed by wind, which affects its beam alignment to the user; equivalently, the user's Signal-to-Noise (SNR). The solution in [74] uses an extended Kalman filter to predict the Minimum Square Error (MSE) of the said beam alignment. It also uses block coordinate descend to determine the optimal number of antenna elements, which governs the UAV's energy efficiency as well as the user's SNR. Another work that uses a Kalman filter is [75], where it proposes to use an unscented Kalman filter to estimate the angle of arrival or angle of departure of a target (receiver) in order to maximize SNR. The solution in [75] incorporates a sensing period to obtain the said angles information, meaning it does not use historical angles information, which is impractical to obtain in practice. In [76], a UAV aims to track a target/vehicle over three stages. In the first stage, it uses a dedicated radar signal to ascertain the following parameters: angle, distance and velocity. In the second stage, it uses a wide beam to better estimate the said parameters. The third stage uses the estimated parameters to form a narrow beam to communicate with the vehicle.

In contrast to the aforementioned works, the UAV in [77] senses a target periodically whilst communicating with a user. Specifically, in each time frame, it senses a target for a fixed duration. The authors of [77] proposed to maximize the user's average data rate by optimizing the following quantities at the UAV: precoding vector, sensing time, and trajectory. A key constraint is that the beam pattern gain at the target must exceed a given threshold. The UAV in [78] is supported by charging stations. Its task is to communicate with a user that has a known location and sense a target with an initially unknown position. To this end, reference [78] considers designing a trajectory that aims to optimize a multi-objective problem comprising of the target's CRB and data rate of the user. Further, the trajectory considers charging station locations, where the UAV is sent to the nearest charging station if it does not have sufficient energy to reach the next hovering point and a charging station.

To date, in this category, there is one work that considers RIS [79]. Specifically, the UAV in [80] has a RIS, where it is designed to sense a ground vehicle at the beginning of each time frame. After that, it communicates with the ground vehicle. The sensing and communication metrics of interest are, respectively, the CRLB of the ground vehicle's estimated position and spectral efficiency. The UAV uses an offline reinforcement learning approach to determine the best UAV trajectory for a given ground vehicle velocity. Given the chosen UAV trajectory, a block coordinate descent method is

then used to optimize the UAV's phase-shift matrix to optimize communication rate.

Lastly, the work in [81] addresses an issue that arises when the trajectory of a UAV is modeled as a set of discrete paths or time slots. This means when a continuous UAV trajectory is required, the problem size and computational requirement increase significantly due to infinite number of paths or time slots. To address this challenge, the authors of [81] transform the problem into a mechanical problem whereby they represent a UAV's trajectory as a catenary or rope hung in an artificial potential field. The resulting problem is then to minimize the overall artificial potential energy on the rope.

1) *Secure Communications*: ISAC is also beneficial in the presence of an eavesdropper. In [82], a UAV communicates with a ground user, aka Bob, which has an unknown trajectory. There is an eavesdropper that moves along a fixed trajectory. The UAV tracks Bob using its communication signals, where it uses an extended Kalman filter to estimate Bob's location. The goal is to optimize the UAV's trajectory in order to maximize its secrecy rate, which is defined as the difference between the data rate at Bob and the eavesdropper [83]. Tong et al. [84] consider UAV trajectory control and transmit power control, where a UAV communicates with a user and simultaneously senses a target. Further, there is an eavesdropper on the ground. To sense the target better, where the SNR at the target is larger than a threshold, the UAV can increase its transmit power or fly closer. However, a higher transmit power reduces the secrecy rate. This means when the eavesdropper is near the user, sensing performance or data rate has to be reduced to avoid information leakage. Reference [85] aims to maximize the average secrecy rate to a user subject to meeting a given sensing rate threshold. To do this, their problem involves optimizing the UAV's trajectory as well as its transmit and receive beamforming vector.

2) *Computation*: Data from the echoes of radar signals have to be processed locally or/and offloaded to another node. In this respect, the UAV in [86] senses a target, computes some data locally and offloads the rest to a ground base station (user) for further processing. To achieve this, it beamforms to both the target and a base station. The sensing metric of interest is the beampattern error, which is affected by the number of antennas, transmit power, and azimuth angle of the UAV. Further, reference [86] also considers the energy consumed by the UAV due to local computation and offloading of data, where it presents a solution that solves a multi-objective optimization problem that trades off sensing performance and energy consumption.

B. Single-User Multi-Targets (SUMT)

There are only two works. Reference [87] considers a UAV with a synthetic aperture radar mounted on its side. There is a user and mobile targets. The proposed solution aims to determine a trajectory that minimizes the energy consumption of the UAV subject to the user receiving a given communication rate and all targets are detected with a certain range and azimuth resolution at all times.

The UAV in [88] provides communication and sensing service to K vehicles, where in each time slot it selects

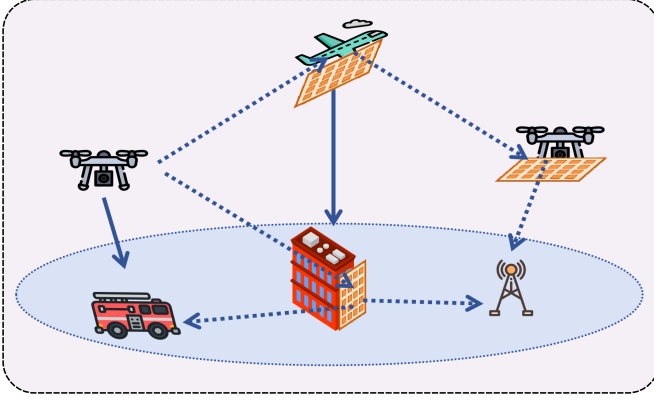


Fig. 4. An example that uses RIS in a UAV network. We use dotted and solid lines to denote RIS-assisted link and normal communication link, respectively.

a vehicle to service. It then decides its transmit power for communication and sensing. Critically, sensing and communication interfere with one another. In this respect, the authors of [88] consider Signal-to-Interference plus Noise (SINR) for communication and radar mutual information [89]. The optimization objective is to determine the sum-rate over a planning horizon.

C. Multi-Users Single-Target (MUST)

In contrast to the previous category, there are multiple users and a target. In this section, all works have the general problem of optimizing a UAV's trajectory, and its beamforming vector in order to guarantee a certain uplink or/and downlink communication rate and sensing performance.

The proposed solution in [90] and [91] aims to guarantee users have a minimum data rate requirement and a minimum target detection probability. To do so, it optimizes the precoding of the UAV's antenna, and its trajectory. Both [92] and [93] assume uplink communications from users using Non-Orthogonal Multiple Access (NOMA). Specifically, the UAV in [92] operates in a maritime environment where it receives data from buoys using NOMA. Further, buoys aim to detect a target cooperatively. In [93], the UAV uses a Kalman filter to track a target, and aims to maximize the sum-rate of uplink communications.

A number of recent works have considered RIS; Figure 4 depicts a scenario where buildings and UAVs have a RIS that can be optimized for sensing and communication. In [94], [95], the proposed solution optimizes the phase shift matrix of a RIS as well as determine the transmitting user in each time slot. The main difference between these works is that reference [94] proposes a reinforcement learning based solution whereas the work in [95] addresses a deterministic optimization problem. In a different work, the authors of [96] consider indoor and outdoor users. More specifically, they consider near-field and far-field radio propagation characteristics when maximizing communication rate and radar mutual information rate.

Reference [97] aims to maximize target detection probability using the generalized Marcum Q-function subject to users receiving a certain data rate, and the sensing power of the target is higher than some threshold. An interesting

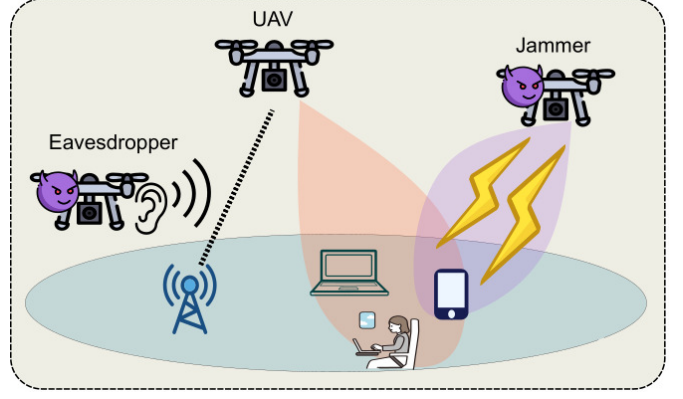


Fig. 5. A UAV network with a mobile eavesdropper and a jammer. The flashes denote jamming signals. A purple beam is a sensing signal.

work is [98], where the authors aim to maximize *effective capacity* [99]; the goal is to find the maximum average data rate that satisfies a given delay. In terms of sensing, the resulting solution must ensure the beam pattern gain at the target exceeds some threshold. Unlike other works, reference [100] considers UAV energy and uplink communications as well as sensing a target with uncertain movement. It proposes to use Long Short Term Memory (LSTM) and historical target trajectory information coupled with reinforcement learning to learn a solution that allows a UAV to minimize its movement or energy cost and maintain a given uplink performance.

There are two works that have considered a bistatic setup, where one or more nodes perform passive sensing in addition to active sensing carried by a UAV. First, the work in [101] considers fusing data acquired by the UAV and a so called terrestrial receive access point (RAP). The target's location is initially unknown. To this end, the UAV first uses widebeam sensing; similar to the work in [76]. After that, it uses a narrow beam to track the target. The second work, namely [102], considers multiple ground access points that act as passive sensors. These access points collect reflection coefficients of the UAV's radar signal. The said coefficients are then sent to an edge server for processing, where it employs the maximum a-posteriori (MAP) ratio test to detect the target.

1) *Secure Communications*: An important consideration is communications in the presence of a rogue node. There are two cases. The *first* case is where there is a rogue or jammer node that aims to lower the communication rate of users. In Figure 5, we see a jammer that aims to reduce the SINR at a user. The *second* case concerns secrecy rate, where a UAV must ensure there is minimum or zero information leakage to an eavesdropper (warden) when communicating with users. Referring to Figure 5, to prevent eavesdropping, a jamming signal or artificial noise will have to be sent in the direction of the eavesdropper to degrade its SINR.

Example works include [103], [104], [105], where a base station aims to maximize the sum secrecy rate when communicating with users. To do this, the work in [103], [104] enlists the help of a UAV with RIS. Specifically, it optimizes the UAV's position, its transmit beamforming vector and jamming power, and the phase shift matrix of the RIS at the UAV.

As for [105], the UAV is not aided by a RIS. Its aim is to ensure a given SNR at a target whilst maximizing the secrecy rate between users and a warden. The UAV in [106], [107] emits jamming signals to interfere with a mobile aerial eavesdropper, where they employ an extended Kalman filter to predict the trajectory of the eavesdropper in future time slots based on signals reflected by the eavesdropper. Then the problem in [106] is to adjust the location of the UAV as well as its beamforming vector in each time slot to optimize its communication and jamming signals.

Another work that considers an aerial eavesdropper or rogue UAV (rUAV) is [108], where rUAV has a full-duplex radio to eavesdrop on transmissions from ground users as well as jam their transmissions. In [108], a UAV communicates with ground users on orthogonal channels, and there is also a base station that receives location information of rUAV from the UAV. In this setup, the goal is to maximize the secrecy rate energy efficiency of users, which is defined by the sum of secrecy rates of users divided by the jamming power used by the base station, transmit and sensing power of the UAV and power used for flight.

In [109], a UAV aims to avoid a terrestrial eavesdropper by using its downlink communications to sense an eavesdropper. The UAV then sends a jamming signal to an eavesdropper's location in order to maximize the secrecy rate of each user. The work in [110] assumes a full-duplex UAV and considers both uplink and downlink communication rates. In addition to a warden, they also consider interfering users. Given this setup, the problem at hand is to optimize the transmission power of users, transmit and receive beamforming vector, UAV trajectory subject to sensing and communication rate exceeding a given threshold, and the target is detected with a given probability.

2) *Computation*: To date, only two works have considered computation in addition to communication and sensing, namely [111] and [112]. To elaborate, the UAV in [111] helps users with their AI inference tasks. It also senses a target using a Kalman filter. In addition, users decide on the importance of features sent to the UAV to ensure a given accuracy. In a different work, the work in [112] requires devices to provide sensing data to a UAV, which runs AI models used for classification. In this respect, a key goal is to minimize the maximum classification errors. To achieve this goal, the solution in [112] optimizes the UAV's transmit power and position, and also the upload time of devices.

D. Multi-Users Multi-Targets (MUMT)

We classify prior works based on their optimization objective(s), namely (i) communication, e.g., sum-rate, (ii) sensing, e.g., beam pattern gain, (iii) sensing and communication, and (iv) energy efficiency, e.g., bits per Joule.

1) *Communication*: References [113], [114] consider optimizing the weighted sum rate of users subject to targets having a minimum beam pattern gain. They first optimize the case with a static UAV followed by the trajectory of a mobile UAV. The UAV in [115], [116] has the option of communicating with a user only in a time slot, or it could conduct sensing and

communication simultaneously. In this respect, given a frame with multiple time slots, a UAV has to decide for each time slot which user or/and target it should sense. Further, it has to ensure each target is sensed once in each frame. Moreover, when sensing a target, the resulting beam pattern gain must exceed a given threshold. For users, the UAV must guarantee a given average data rate.

The work in [117] also considers sensing frequency during uplink and downlink communications. Its UAV uses time division duplex to facilitate uplink and downlink from/to users. Further, in some downlink time slots, it may use an ISAC signal to sense targets. In addition, the UAV only senses targets depending on sensing errors; this is unlike the UAV in [113], which assumes periodic sensing. The UAV in [118] has monostatic side-looking synthetic aperture radar, where it schedules a user to upload in each time slot, optimize its transmit power and trajectory to either maximize sum-rate or the maximum minimum data rate of users. The UAV in reference [119] aims to detect blockages using ISAC in order to maximize sum-rate. Its main decisions include transmit power and beamforming vector to ensure there is no interference between communication and radar signals.

In order to improve coverage, a number of works enlist the help of a UAV as a relay or a UAV with a RIS. For example, the UAV in [120] functions as a relay between a base station and ground users. In this respect, the work in [120] considers end-to-end communication and sensing performance between users and a base station. In particular, it allocates different sub-carriers for communication and sensing; a separate set of sub-carriers are used for two types of links: communication between the base station and UAV, and between the UAV and users; i.e., one set of sub-carriers is used for sensing by the UAV, and another set is for transmitting sensed data from the UAV to the base station. The authors of [120] formalized a problem that aims to optimize the transmit power over each sub-carrier to maximize the minimum data rate over links used to carry user data. Further, they ensure the mutual information rate of targets exceeds a given threshold.

The base station in [121] aims to communicate with multiple users and targets. To this end, it aims to optimize the sum-rate of users by optimizing its beamforming vector and also optimizing the trajectory of an RIS-equipped UAV; hence, a key optimization variable is the phase shift of the RIS. The work in [122] also considers RIS, where it aims to maximize the sum rate of users. To do that, it optimizes the UAV's trajectory, beamforming matrix at the UAV and RIS using a hierarchical reinforcement learning approach subject to constraints that ensure a given beam pattern gain and radar signal echoes meet a given average SNR. Lastly, reference [123] considers secure communications using a UAV aided by a RIS. It also considers a challenging aspect, where the UAV does not have channel state information to an eavesdropper when serving users and sensing targets. It detects one target and communicates with one user at a time. In addition, it communicates with users using power domain NOMA.

The work in [124] also considers NOMA, where its goal is to study how ISAC can replace pilot symbols for channel estimation. It considers a UAV that senses the position and

velocity of users using Orthogonal Time-Frequency Space (OTFS) [125]; the UAV has two UPAs for transmitting and receiving OTFS signals and echoes respectively in order to derive a receiver's location. It then uses power domain NOMA to communicate with users, where allocates its transmit power accordingly to enable decoding at each user. Further, reference [124] studies the case where the UAV has perfect or imperfect channel information to users.

Similarly, the work in [31] uses ISAC to replace pilot symbols for channel estimation. To elaborate, a UAV uses a two phase process, where it first uses a wide beam to discover targets. After that, it uses a narrow or directional beam to track targets using an extended Kalman filter to predict the azimuth, range, and velocity of targets. In addition, they consider maximizing the sum rate to users subject to them receiving a minimum data rate and the beam pattern used has a given angle and beamwidth.

2) *Sensing*: Some works aim to maximize sensing performance subject to users meeting a given data rate. To do this, reference [126] ensures a desired beam pattern for tracking targets by optimizing the covariance matrix of its UAV's radar signal. The work in [68] also considers 3D array steering; i.e., its UAV changes orientation via its onboard gimbal, meaning the UAV has to optimize its spatial orientation to maximize sensing performance.

The UAV in [127] searches for targets in an area divided into sectors; each sector has a central direction and width. In this respect, reference [127] aims to design precoders for communications and sensing that minimize the mean square error of each sector's transmit beam pattern and ensure users experience a given SINR. Moreover, they must result in minimal mutual interference. In [128], the UAV optimizes its beamforming vector to take advantage of a RIS in order to maximize the minimum beam gain at targets.

3) *Multi-Objectives*: In this section, we discuss works that aim to balance sensing, communication and/or energy concurrently, where they address the challenging problem of optimizing resources, e.g., transmit power or antenna elements, to balance multiple performance objectives.

The UAV in [129] collects data from users with an unknown location. Further, the priority of a user is set to its queue length to avoid data loss. The UAV uses deep reinforcement learning to seek users in a manner that maximizes a reward that is related to communication rate, target detection, queue overflow and flight. Instead of focusing on users, the work in [130] considers traffic demands from a set of areas. For each area, it considers the worst and best conditional mutual information [131], which is a function of a UAV's position and transmit power; it also considers factors including antenna gains and operating frequency. It then formulates a robust optimization model using the framework in [132], whereby a computed solution allows up to a certain number of constraints to be violated. The decision variables to be optimized include whether (i) a UAV is deployed at a given location, and (ii) a sub-carrier is used for sensing or communication.

There are two works that consider a UAV that charges users. Specifically, the UAV in [133] charges users and aims to maximize their sensing Signal-to-Interference plus Noise

Ratio (SINR) and the minimum uplink data rate of users over multiple time slots. Further, it optimizes the (i) uplink duration of each user and its transmit power, and (ii) number of radar sequences, and filter used to process echoes. The UAV in [134] charges users when it beamforms to sense targets. Users then upload their data to the UAV as per their harvested energy; the UAV then forwards the received data to a gateway. It also optimizes transmit power to maximize the sum-rate of users and mutual information sensing rate of targets.

The following works divide a UAV's trajectory into segments, which help reduce computation cost. In [135], the UAV considers the average and worst case CRLB of targets as well as the communication rates of users. To guarantee a given CRLB of targets, it needs to visit at least three hovering points. The optimization problem then aims to determine these points and flight time of each segment, i.e., time between two hovering points. In a different work, the UAV in [136] helps relay data to a satellite, where its data is obtained from users as well as from sensing targets; both users and targets are static. In each segment of its trajectory, the UAV has to determine whether users should upload their data to the (i) UAV, (ii) satellite directly, or (iii) satellite via the UAV, or (iv) task the UAV to acquire sensing data. The goal is to maximize the amount of sensing and communication data.

The focus of reference [137] is on waveform design to facilitate sensing and communication, where they aim to design a waveform that mitigates multi-user interference and beam pattern mismatch. To this end, it considers optimizing the waveform used by a stationary UAV aided by a RIS, where the problem at hand is to select a waveform and phase shift matrix that minimizes inter-user interference and beam mismatch at targets. The performance objective comprises of both communication and sensing performance. The main constraints relate to transmit power, peak amplitude to average power ratio, ideal beam direction and a so called constant mode constraint that ensures the RIS does not change the amplitude of the reflected signal.

The UAV in [138] works in a multi-cell network, where it uses Orthogonal Frequency Division Multiple Access (OFDMA) and Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surfaces (STAR-RIS) [139]. It aims to improve the SNR of users at the cell edge and also simultaneously sense targets within the cell. In this respect, the main performance metric relates to the sum-rate to users located at the cell edge, and the amount of sensing data acquired by the UAV. To do this, the optimization variables include beamforming vector, transmission and reflection matrix of the RIS, subcarrier allocation for user and sensed data. In contrast, the fixed-wing UAV in [140] considers a single cell and uses Rate Splitting Multiple Access (RSMA) [141], [142], [143]. Briefly, in a RSMA system, see Figure 6, users first decode the common part of a transmitted message. Its common part is then subtracted from the received signal. After that, a user decodes the private part of its message by treating the private part of all other users as interference. The UAV in [140] operates in two phases, where it first senses users followed by communication with users and a gateway. In this second or communication phase, the UAV has to select a

user and also determine a common rate to facilitate RSMA. The performance objective is to maximize the minimum radar information rate and weighted sum-rate.

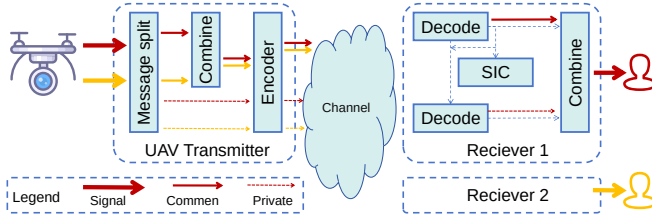


Fig. 6. UAVs in RSMA systems.

Only one work has considered fairness, where the UAV in [144] aims to maximize the minimum fairness index or Jain's fairness index of both the communication and sensing rate of users and targets, respectively.

4) *Energy*: There are two sets of works: (i) energy efficiency, which is defined as the amount of data transmitted per unit of energy, and (ii) total energy consumption, which includes the energy cost of communication, sensing and flight.

To date, there is one work that considers RSMA [141] and energy efficiency. In [145], the UAV maximizes its location, precoder (beamforming) and common rate of each user in order to maximize energy efficiency. The sensing performance metric of concern is beam pattern error. Reference [146] also has a similar formulation, where it incorporates constraints that ensure the CRLB of targets' estimated azimuth and elevation angle does not exceed a given bound.

The UAV in [147] helps a base station relay data to users in communication time slots; note, the same authors consider the case without a relay in [148]. The UAV then collects echoes in sensing slots, where it then compresses the resulting sensed data before forwarding it to the base station. The authors of [147] also proposed to design the beam pattern used for sensing targets offline. The UAV then optimizes its transmit power in the online stage when it hovers on top of a target. We note that similar to [117], the authors also optimized which time slots are used for sensing. Given this setup, the problem at hand is to minimize the UAV's total energy consumption, which is determined by the transmit power it uses to transmit to users and sense targets, and also communicate with the base station. Other factors include flight, circuit power and computation. Their optimization problem also ensures targets and users receive a certain level of performance. Further, it ensures the UAV has sufficient capacity to upload its sensed data to the base station. In contrast to the non-relay case in [148], the UAV's energy consumption is only due to beamforming, hovering and flight.

Reference [149] considers service placement, task offloading, and adaptive compression. To elaborate, a UAV helps processes tasks from users, and also senses targets. The UAV is supported by a high altitude platform that has a library of services, where the task offloaded by a user requires one of these services. Apart from that, users compress their data if they decide to offload to the UAV. The aim of [149] is to minimize the total energy consumption of the HAP, UAV and

users, which is attributed to the transmission and computation of tasks or services, and flight.

The work in [150] considers a different definition of energy efficiency. In particular, it is a ratio between (i) the sum of sensing score that correlates with the distance between a UAV and a target and its priority, and (ii) the total energy consumption of the UAV. To this end, the reinforcement learning based solution in [150] aims to learn a policy that controls the velocity and direction of the UAV to maximize the said sensing score and minimize its energy consumption in a environment with fixed targets and mobile users.

5) *Others*: The work in [151] considers the average transmission time required to transmit data from a UAV to each user. Unlike the aforementioned works, the UAV of [151] considers the properties of terahertz signals during communication and sensing. Its decision variables include the sub-carrier assigned to each user and corresponding transmit power.

E. Target(s) Only

This section only discusses works that employ ISAC in order to sense one or more targets; there are no ground users. A UAV, however, may communicate with a base station or other UAVs to transmit/receive sensed data. Note that many works, e.g., [8], [152], use the term *sensing* in a generic sense; i.e., their work is applicable for any types of sensors. However, they do not consider issues that arise when sensing and communication signals have to coexist on the same channel; we thus omit them from our discussion.

1) *Sensing Only*: An important metric is the Age of information (AoI), which measures data freshness [153], [154]. The order in which a UAV visits targets affects data freshness as it determines when a sample of a target is collected by the UAV. Both [155] and [156] consider a UAV that aims to minimize the peak age of information of all targets. The UAV senses one target at a time and the CRLB of the target estimated position is below some threshold. In addition to a UAV's location, other system parameters to be optimized include the transmit power and time used for sensing and communication. In both works, they assume there is no interference when sensing a target and all targets are static.

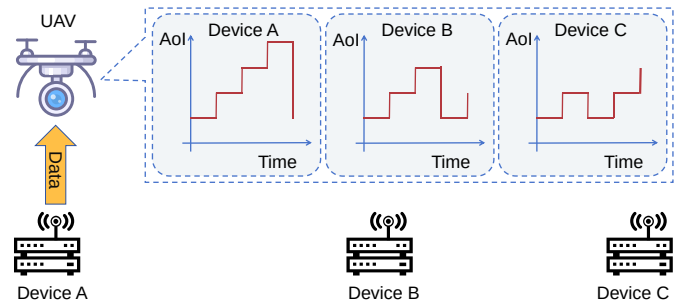


Fig. 7. An example where a UAV uses the AoI metric to determine its trajectory to collect/sense devices.

There are two works that consider targets detection probability. In [157], the UAV aims to detect targets and transmits its results to a base station. The probability that a target is

detected is dependent on the received power of echo signals. If a target is detected, then sensed data is queued at the UAV. A sub-problem then is to determine when to transmit sensed data to a base station. The authors of [157] aim to optimize the cumulative target detection probability, amount of data transmitted to base stations, and UAV's energy expenditure.

Second, reference [158] considers a UAV that operates in a cellular network. The UAV transmits its collected data to a base station. Critically, the UAV must not cause interference to users. Similar to the works above, sensed data is generated when a target is detected. The probability of target detection is determined by the UAV's transmit power and location. The key optimization variables include the UAV's transmit power, targets to be sensed, sensing duration, and UAV location.

The work in [159] considers a UAV that tracks a target using an extended Kalman filter. In particular, they improve upon the work of [160] where they developed a new energy-efficient algorithm to improve the CRLB of a target's estimated state; see Section III-D3 for further details. Similarly, reference [161] considers the use of a Kalman filter to track a target's position and velocity. Here, the performance metric of interest is the weighted posterior Cramér-Rao Bound (PCRB) of the target's position and velocity. To do so, they proposed a Kalman filter based solution to optimize the UAV's position and velocity along a horizontal axis.

Both [162] and [163] consider radar mutual information rate [89]; it is similar to communication rate as computed using the Shannon-Hartley theorem but uses the SNR of radar signals. To this end, reference [162] aims to maximize the sum of radar mutual information rate of targets [163], where a UAV visits targets and transmits sensed data to a base station. On the other hand, in [162], the authors consider energy efficiency, which is equal to the sum of communication rate to a base station and radar mutual information rate. They also consider the minimum radar mutual information rate of users. In both works, the key decision variables include user scheduling, i.e., whether samples are collected from a user, UAV transmit power, and UAV position.

2) *Sensing + Computing*: Similar to works on radar mutual information rate, e.g., [162], [163], the UAV in [164], [165] samples one target at a time and offloads sensed data to a base station with an edge server. In these works, the UAV optimizes its trajectory, deciding whether to use a time slot for sensing a target and the total number of time slots used to collect samples. To elaborate, the work in [164] aims to minimize the average age of information of targets. A key constraint is that each target must have a radar mutual information rate that is above a given threshold. On the other hand, the UAV in [165] aims to minimize the total energy consumed by sensing, communication with a base station, and flight. In addition, for each target, it also considers the number of samples required to achieve a given training error at the base station; the number of samples is proportional to the target's radar information rate.

The fixed-wing UAV in [166] senses targets, where it sends the echoes of its radar signals to an edge server, which then returns the result to the UAV. In this setup, the problem at hand is to jointly determine the beam pattern vector at the UAV and its trajectory to maximize the amount of data

computed by the edge server. The targets in [167] have an unknown location, which affects the sensing rate of targets and the amount of data offloaded to an edge server for processing. To this end, the authors of [167] propose to use a reinforcement learning solution to minimize the UAV's flight time in order to sense all targets. Similarly, the target in [168] has a random mobility, where a UAV aims to track to sense and transmit the resulting data to an edge server. In this respect, the UAV uses a reinforcement learning solution to control its motors as well as its sensing and communication rate.

The UAV in [169] optimizes its beamforming vector toward access points with a server and a target. A key requirement is that the signal power at the target must exceed a given threshold. To this end, the UAV aims to optimize its beamforming and trajectory to jointly maximize the (i) average amount of data offloaded to access points, which is constrained by their computation capacity, and (ii) average signal power at a target. In [170], the authors consider a similar problem but their UAV is able to carry out computational locally as well as offload it to a ground access point. In this respect, they aim to maximize energy efficiency, which is equal to the total amount of sensed bits computed by a UAV and access point divided by the energy consumed by the UAV.

In the area of Multi-access Edge Computing (MEC), UAVs have been considered as mobile servers that help resource constrained devices compute data; see [171] for a survey. With respect to ISAC, there are two works to date. First, in [172], a UAV helps ground devices compute sensed data of targets. These devices beamform to the UAV and their targets to obtain data. Their sensed data is then computed locally or offloaded to the UAV. To ensure their data upload does not interfere, devices employ NOMA. Apart from that, devices must ensure a given beam pattern gain at their targets. The authors of [172] formulated a multi-objective optimization model that aims to minimize beam pattern errors at targets and maximize the minimum amount of sensed data by computed devices. Second, in [173], a base station senses for active ground devices to aid a UAV. The proposed solution then optimizes the offloading decision of active devices, sensing threshold of the base station, which determines how many devices it can detect, and time allocated to active devices to upload their data.

3) *Bistatic*: A UAV and a base station can collaborate to form an synthetic aperture radar, which helps increase sensing resolution. Further, as the UAV is passive, it does not introduce any interference. To this end, a number of works use a UAV to collect the echoes of signals transmitted by a base station. In [174], the authors aim to sense known targets using communication signals emitted by a base station and a UAV. Specifically, given these communication signals, they aim to compute a UAV trajectory that uses the minimum propulsion energy to collect echoes of the said signals from targets. Further, the computed trajectory must ensure a given sensing resolution performance in terms of azimuth and range of targets, detect all targets, and UAVs fly a certain speed.

The authors of [175] studied a similar UAV-aided bistatic system but with a mobile target. They studied a new UAV navigation law that ensures the sensing performance of a

mobile target in terms of its range and azimuth resolution will exceed a bound after some time period. Reference [176] further considers offloading of data to a base station, where a UAV must ensure it has sufficient backhaul link capacity to offload sensed data. The optimization objective is to minimize energy due to flight and communication cost.

Different from the aforementioned works, the UAV in [177] is responsible for illuminating targets using Orthogonal Frequency Division Multiplexing (OFDM) signals. The echoes of these signals are received by a ground base station that has two antenna arrays, one that receives reflected signals from targets, and the other is used to receive ISAC signals from the UAV for synchronization and interference mitigation. Note that the work in [177] is on waveform design and signal processing as opposed to resource allocation or UAV trajectory design.

F. Observations

Table III shows a high level comparison of single UAV works. The UAV in all works travels at a fixed altitude/height. A common constraint is that the velocity of the UAV must not exceed a given maximum value. Further, no works have considered obstacles when planning a UAV's flight. Most works only optimize a UAV's coordinate. To date, only references [178] and [168] have considered a UAV's attitude. In general, they assume a quad-rotor UAV. Only works such as [120], [91], [140], [166] have considered a fixed-wing UAV; this assumption only changes a UAV's energy consumption model. All works assume nodes are static in each time slot, which helps avoid complications with Doppler shift. Except for [80], [109], [169], [170], all works equip their UAV with a ULA.

A majority of works focus on downlink communications to users. This is reasonable given that communication signals are used for sensing. Only reference [117] has jointly optimized uplink and downlink communications from/to users. In terms of energy consumption, only slightly more than half of the discussed works consider energy. The majority of these works are in Section II-D. To date, only two works have considered the energy of users, namely [133], [134], where they harvest RF energy from a UAV. In contrast, the work in [78] considers a UAV supported by a mobile charging station.

In wireless networks, interference is a fundamental issue, where there is mutual interference between users and also between sensing and communication signals, e.g., [88]. For uplinks from users, channel access is required, e.g., see the section on MUST, and MUMT, to coordinate transmissions from users. Further, clutter or other targets may interfere with sensing accuracy. Most works use a separate time slot dedicated for each user as well as for sensing. Hence, a key problem is user or/and target selection. In terms of communications, some works assume a UAV with full-duplex capability, e.g., [110], RSMA, e.g., [140], [145], [172], or NOMA, e.g., [92], [93], [123] and [124]. It is worth noting that all works that employ RSMA and NOMA assume a known decoding order based on the strongest to weakest channel gain. However, in practice, determining this order is an NP-hard problem, see [142], [179], [180] for example works. For works that use a full-duplex UAV, RSMA or NOMA, a key consideration

is mutual interference between users, which requires careful transmit power control.

Fairness is also important, where users must have similar communication rate, and targets are sensed in a fair manner. Only references [90], [91], [121] have considered maximizing the minimum data rate of users in order to ensure fairness. Otherwise, they optimize sum-rate, age of information or amount of sensed data. To date, only [144] has considered fair sensing rate. Otherwise, prior single UAV works, e.g., [90], [147], ensure targets have a minimum sensing performance.

In terms of target tracking, most works assume known target locations or mobility. Otherwise, a standard approach is to employ a Kalman filter or/and reinforcement learning, e.g., [73][74][80][100]². Another observation is that the works in Section II.D (MUMT) and Section II.E (Target(s)) do not consider tracking *multiple* moving targets concurrently.

Table IV shows the common resources that are optimized by the solutions in prior works; they apply to both single and multi-UAV works. On a UAV, the main decisions include its trajectory, where most works optimize its (x,y) coordinate on a given plane (or altitude), transmit power and beamforming vector. Its flight duration or trajectory is affected by its on-board energy, and vice-versa. Further, its trajectory will impact communication and sensing rates as both quantities are dependent on the distance to a user and target. These rates can be improved with the aim of an RIS. In this case, a solution will have to optimize the phases used by a RIS, UAV(s) position, and beamforming vector of UAV jointly; in the case of uplink transmissions, then users will have to optimize their transmit power to ensure decoding success.

In terms of the channel, the majority of works assume time division multiplexing, where sensing and communication operations are carried out in a separate time slot. Further, they may assume these operations are on an orthogonal channel that is either pre-assigned to a UAV or user, or assigned dynamically. Apart from time and channels, recent works, e.g., [140], [92], [93], have used RSMA or NOMA, which requires the transmit power of UAVs or users to be optimized to facilitate decoding.

III. MULTI-UAVS NETWORKS

A natural progression from the single UAV case is to consider deploying multiple UAVs to communicate with more users, or/and allow collaborative sensing of targets. Figure 8 shows example scenarios involving multiple UAVs, which bears resemblance to the single UAV case, see Figure 2. As we will see later, UAVs can take different roles, where a UAV can be tasked with receiving or computing sensed data/echoes or to jam eavesdroppers. Further, the main differences to the single UAV case include (i) *user or target association*, where users or targets must be grouped around UAVs, (ii) *interference*, where ISAC operations of UAVs may interfere with one another, see [181] for an analysis on interference based on stochastic

²Note, all works that use a reinforcement learning solution modeled their problem incorrectly, where they formulated a one shot or deterministic optimization as opposed to a sequential decision making problem or stochastic game that aims to compute a policy that maps a state to an action.

TABLE III

A HOLISTIC COMPARISON OF SINGLE UAV WORKS. THE NUMBERS IN THE FIRST ROW INDICATE THE NUMBER OF PAPERS. EACH CIRCLE SHOWS THE PERCENTAGE OF PAPERS THAT HAVE A GIVEN FEATURE, WHEREAS A FILLED (BLACK) CIRCLE (100%) DENOTES ALL PAPERS HAVE A FEATURE.

Features	SUST (18) (Section II.A)	SUMT (2) (Section II.B)	MUST (24) (Section II.C)	MUMT (39) (Section II.D)	Target(s) (21) (Section II.E)
2D Trajectory Planning	●	●	●	●	●
Static User(s)	○	○	●	●	N/A
Mobile Target(s)	●	○	○	○	○
Downlink Communications	●	●	●	●	●
Energy Consumption	○	○	○	○	○
Fairness	○	○	○	○	○
Quad-Rotor UAV	●	●	●	●	●
Backhaul Link	○	○	○	○	○

TABLE IV

A HIGH LEVEL OVERVIEW OF RESOURCE ALLOCATION IN SINGLE AND MULTI-UAVS WORKS. THE STATED VARIABLES ARE DETERMINED BY SOLVING AN OPTIMIZATION MODEL OR USING A REINFORCEMENT LEARNING APPROACH.

Components	Variables	Comments
UAV	(x,y) coordinate	A UAV's position over time at a given altitude.
	Velocity	A problem is to determine a UAV's velocity between waypoints.
	Beamforming vector	This is optimized to ensure high SNR at users or/and targets.
	Precoding matrix	As above, and usually optimized for both sensing and communication.
	Energy	This impacts a UAV's flight path and duration, and its transmit power.
RIS	Phases	Amplitudes are usually fixed in prior works.
Channel	Time	A key problem is to allocate communication and sensing time. Another is user scheduling, and whether a time slot is used for uplink, downlink or sending
	Sub-carrier	A key problem is selecting users.
Users	Transmit power	This impacts SNR at UAV and at an eavesdropper.
	Energy	This bounds a user's maximum transmit power.

geometry, (iii) *flight safety*, where UAVs must be at a safe distance from one another or/and be position at some minimum distance to a target or obstacle. In terms of resources, multi-UAVs works also optimize the same resources listed in Table IV. They also have the same performance objectives/metrics as those in Table II; e.g., sum-rate, SINR or SNR at target(s) and radar mutual information rate [182].

We also point out that many works have considered using UAVs to track one or more mobile targets. They, however, assume generic sensor technologies, e.g., [183]. For recent surveys that involve the use of UAV swarms to track targets, we refer the reader to [184], [185]. We stress that they are not focused on employing ISAC. Hence, they are omitted from our discussion below.

A. Single User Single Target (SUST)

Both [186] and [187] used an extended Kalman filter to track a mobile target. Specifically, in [187], UAVs process the echoes of their radar signals when they transmit to a base station to estimate the velocity of a mobile target. By contrast, in [186], multiple UAVs illuminate a target, where

echoes are processed by a ground base station to determine the location of the target. The distributed sensing algorithm in [188] allows UAVs to track a moving target based on each other's transmissions. Each UAV decides its position based on the target's location and also the location of other UAVs in each time slot in order to improve target localization accuracy. After that, each UAV decides its transmit power sensing and communication. Lastly, the three UAVs in [189] use a decentralized partially observable Markov decision process (Dec-POMDP) approach to optimize their waveform in order to detect a target.

A number of works use a central node to coordinate UAVs or to receive sensed data. In [190] and [191], a fusion center schedules the deployment of UAVs to search and estimate the position of a static point-like target in their assigned area. UAVs then optimize their beamforming vector to sense targets and communicate with other UAVs.

B. Single User Multiple Targets (SUMT)

The UAVs in this section sense targets and communicate with an aerial or ground user concurrently. Further, targets

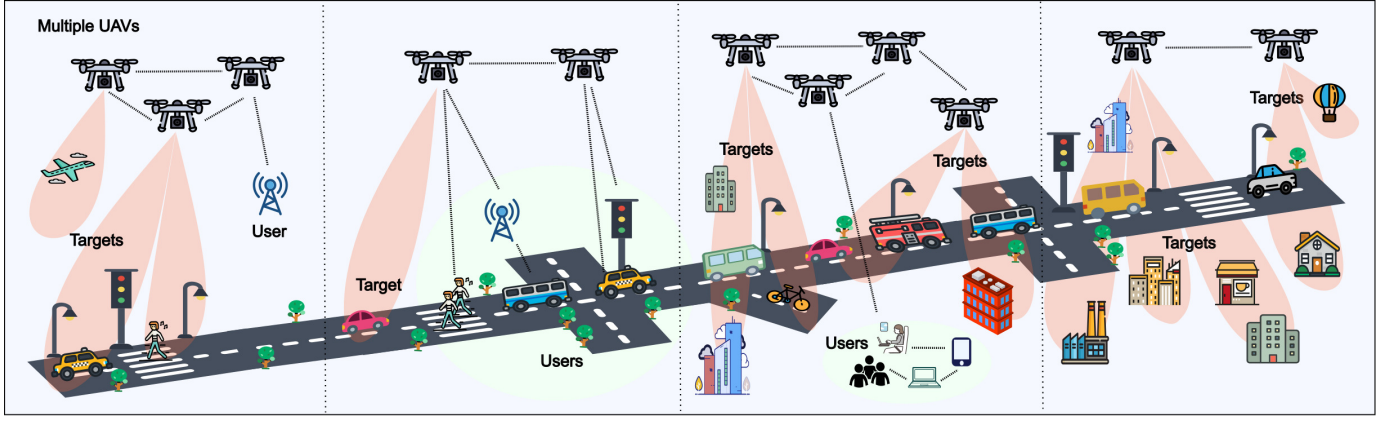


Fig. 8. Different scenarios with multiple UAVs. Recall that solid lines represent communications, and orange beams denote sensing. In each scenario, multiple UAVs must collaborate to sense one or more users or/and targets.

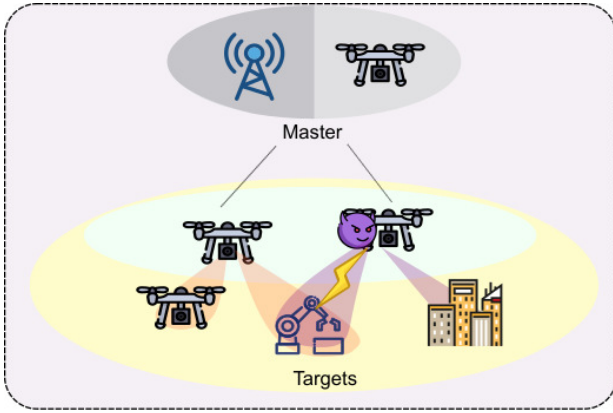


Fig. 9. An example of a two-tier network.

may be other UAVs. To monitor targets, a few prior works adopt a two-tier network comprising of UAVs with a different role. Specifically, there is a master node (user), either a UAV or ground station, that is responsible for processing sensing data. Figure 9 shows an example where a master node located at *Tier-1*, either a terrestrial base station or a UAV, controls other UAVs located at *Tier-2*. Next, we divide prior works according to whether a user is aerial or terrestrial.

1) *Aerial*: In [192], designated secondary UAVs monitor ground areas and transmit their sensed data to a master UAV (user) for processing. Further, the master UAV senses secondary UAVs. The authors of [192] carried out an analysis to determine the average mutual sensing interference and communication capacity, cooperative range of UAVs, and their impact on performance metrics such as the total area covered by secondary UAVs and communication outage capacity.

Similarly, reference [193] has two tiers of UAVs. The UAVs at tier-2 sense targets, which may belong to different priority classes. These UAVs send their data to a master UAV or user at tier-1. Given this network, the authors of [193] studied packet scheduling policies such as First Come First Serve (FCFS), and their impact on the age of information of targets. They also studied the impact of factors such as link and node outage, which results in packet loss.

Both [194] and [195] consider computation, where the UAVs at tier-2, called secondary UAVs (sUAVs), send their radar data to a central/master UAV or user for processing. The aim is to maximize a utility that is attributed to (i) service success, which is defined as the number of targets in which a certain amount of data is collected and its radar mutual information rate is higher than a given threshold, and (ii) energy consumption of UAVs, which includes communication and computation cost.

The user in reference [196] is a high altitude platform [196]. It collects and processes radar data from UAVs. In this respect, the total amount of radar data is determined by the transmit power used by UAVs to transmit radar signals, their energy and distance to targets, and also the link capacity between UAVs and the central node. There is no interference, where the central node ensures only one UAV transmits. Further, the solution in [196] aims to optimize energy efficiency.

Lastly, the work in [20] considers a swarm of UAVs with a master UAV that follows a flight path. UAVs aim to avoid obstacles as well as each other. In this respect, UAVs use ISAC and treat obstacles as virtual targets; specifically, UAVs use the demodulation reference signal of OFDM to estimate the range and radial velocity of obstacles. A master UAV then fuses sensed data to generate virtual targets, which are then used by other UAVs to maintain their flight path.

2) *Terrestrial*: Unlike the works above, the UAVs in [197], [198] monitor targets and transmit their data to a terrestrial base station or fusion center (user). The work in [197] considers the number of target samples, where it uses Jain's fairness index to ensure all targets have similar number of samples. To collect samples, the UAVs in [197] use a Multi Agent Reinforcement Learning (MARL) approach to determine their trajectory, transmit power for sensing and communication, and channel assignment. Critically, a feasible solution must ensure that the SINR at targets and the data rate at the fusion center exceed a given threshold. By contrast, the work in [198] considers minimizing the time required to obtain and process a given amount of sensed data from all targets. It uses an optimization approach with an online stage to cluster targets and determine the trajectory of UAVs. Then in the online stage,

their approach optimizes the transmit power of UAVs.

The UAVs in [199] employ a MARL approach to optimize the policy used by UAVs for monitoring targets and also to maintain connectivity to a base station. In particular, the policy aims to minimize the distance of a target to a UAV, which helps improve sensing rate, and the energy used by UAVs. Reference [200] also considers a MARL approach, where a central UAV and secondary UAVs aim to maximize a utility that is a function of whether a target is detected by a secondary UAV, data rate of secondary UAVs and their energy. In addition, they also consider completion time, which corresponds to the time taken to detect targets and communicate with the central UAV. Unlike the previous two works, the MARL solution in [201] considers targets with different task types, namely detection or localization; a detection task requires one UAV whilst localization task requires multiple UAVs. In addition, the solution also considers the sensing interval of tasks.

In [202], UAVs are used to monitor mobile ground vehicles (targets), e.g., in a city, where they send their sensed data to a base station (user). All communication and sensing signals are on an orthogonal channel. Given this setup, the work in [202] aims to discover a policy via reinforcement learning that maximizes the sensing rate and coverage of targets, and also minimizes the energy usage of UAVs. Advantageously, the policy also considers a novel metric that quantifies fairness, amount of data and quality of targets, which includes the case with redundant coverage, where a target may be within the beam of multiple UAVs.

Only two works, namely [203], [204], in this category have considered secure communications. Both works consider a UAV (Alice) that aims to communicate with a terrestrial user called Bob, and also sense multiple targets. Further, there is an eavesdropper. UAV (Alice) is aided by another UAV called UAV (Jack) that jams the eavesdropper and help UAV (Alice) detects targets. In particular, UAV (Jack) can jam the eavesdropper when UAV (Alice) communicates with Bob, and also uses its jamming signal to help sense targets. Both works aim to optimize secrecy rate by optimizing the beamforming vector at UAV (Alice) and UAV (Jack) and also their trajectory.

C. Multi-Users Single Target (MUST)

In [205], UAVs optimize their trajectory, user association and beamforming to maximize the sum-rate of users. All UAVs operate on an orthogonal channel. On the other hand, the UAVs in [206] operate on the same channel, serve users using RSMA [141] and also maintain a minimum sensing performance, namely SINR, at a target. To this end, a key problem is to allocate users into a group, which is then managed by a UAV. Further, messages are divided into a common and private part, with a respective common and private data rate. In this respect, the UAVs in [206] aim to maximize the weighted sum-rate of users; note that each user rate includes the common and private data rate. Further, the common rate of all users is the same and determined by the user with the worst channel condition. The third work, namely [207], considers a central UAV that coordinates the communication and sensing tasks of M other so called edge

UAVs. Further, there is a jammer UAV that aims to degrade the communication link from edge UAVs to users. The edge UAVs aim to maximize the total data rate across all users and also ensure the sensing performance between each edge UAV and its associated users is above a threshold.

In the following works, UAVs have a backhaul link to a base station, where they aim to maximize the sensing performance of a target. To elaborate, in [208], multiple UAVs aim to sense a target, where a designated UAV collects echoes after other UAVs transmit. Further, the link between UAVs and users, and UAV to a base station, which has a ULA, operate on a separate frequency. The problem at hand is to maximize the SINR of a ground target by optimizing the transmit beamforming vector of the base station and UAVs, receive beamforming vector of the base station, and position of UAVs.

Reference [209] considers an OFDMA network with multiple UAVs and base stations (users), and a rogue target/UAV. UAVs aim to determine the location of the rogue UAV, collect echoes, and upload their data to a base station for processing. A key problem is associating each UAV to a base station and also assigning them one or more sub-carriers. The performance metric of interest is the CRLB of the rogue UAV's estimated location. To optimize this metric, the authors of [209] optimize the trajectory of UAVs, the number of subcarriers (or bandwidth) assigned to each UAV and corresponding transmit power, and the association between a UAV and a base station. In both works, a key constraint is to ensure the backhaul link used by UAVs has a minimum communication rate.

Besides the above works, references [210], [211] aim to maximize the minimum detection probability of a target. Further, they aim to ensure users have a minimum SINR or data rate. The main difference between them is that the solution in [210] only considers placement and transmit power of UAVs whereas the UAVs in [211] also optimize their beamforming vector.

Lastly, reference [212] considers clutters/blockages where UAVs transmit over a millimeter wave channel. Its goal is to maximize signal-to-clutter-plus-noise ratio. In addition, it aims to maintain a minimum SNR at users. To do that, it optimizes the transmit and receive beamforming vector at UAVs as well as the trajectory of UAVs.

D. Multi-Users Multiple Targets (MUMT)

We first discuss works that aim to maximize communication rates followed by those that focus on sensing. This is then followed by works that aim to maximize both communication and sensing concurrently. Lastly, we will discuss works that consider other metrics, e.g., total energy consumption, and age of information to name a few.

1) *Communication*: A standard performance metric is the weighted or total sum-rate of users. As we will see later, this metric is affected by UAV positions and their transmit power, sensing errors, and interference caused by friendly or rogue UAVs to name a few. Apart from that, all works in this section have a constraint that ensures sensing accuracy meets a given requirement, i.e., the CRLB of the estimates corresponding to the location of targets is below a given accuracy threshold.

We start with works that involve so called *helper* UAV(s). First, the full-duplex UAVs in [213] act as relays for a base station, where they help broadcast the base station's signals to their associated users. Further, when relaying signals, UAVs act as a distributed MIMO radar to sense targets; specifically, their distance and radial velocity. The problem at hand is to optimize the location and transmit power of UAVs, and UAV-user associations. Reference [214] also considers relaying of traffic from users. It uses two UAVs, namely UAV-s and UAV-r (helper). UAV-s serves ground users where it helps relay their traffic via UAV-r to a base station. To do this, UAV-s first senses ground users to determine their location; specifically, it estimates the angle-of-arrival of their signals. After that, UAV-s optimizes its receive beamforming vector and its trajectory to maximize the weighted average sum-rate of users.

Past works have also aimed to maximize secrecy rate. In [215], there is a source UAV that communicates with users. Further, there are multiple eavesdroppers (targets) and a jammer UAV (helper). To communicate, the source UAV first senses the location of eavesdroppers. This information is then sent to the jammer UAV. The problem at hand is to optimize (i) user selection, where the source UAV can only transmit to one user in each time slot, (ii) UAV transmit power, and (iii) UAV trajectory. The main constraints relate to the SNR at eavesdroppers to facilitate sensing, and the communication rate between the source and jammer UAV must exceed the amount of sensed data. Note that the jammer UAV is stationary.

The UAVs in [216] also have to operate in the presence of eavesdroppers in order to maximize the secrecy rate of users. To this end, their reinforcement learning based solution learns a policy that optimizes the beamforming vector of UAVs, and user-UAV associations. The work in [217] considers users who require different contents in the presence of aerial eavesdroppers. To this end, UAVs have to decide on downloading and store contents from a server, and deliver them to users. Hence, similar to prior works, maximizing secrecy rate is important. It is also worth pointing out this work is related to research on caching and service placement in UAV networks; see [4].

Another concern is the fairness of user data rates. In this respect, the authors of [218] maximize the minimum data rate of users. In each time slot, there is a sensing and communication phase. Further, UAVs have to select a user to serve. In addition, they adopted radar mutual information rate [182] and ensure their solution meets the average radar mutual information rate of each user exceeds a given threshold; this is similar to their other works, see [163]. To do so, UAVs have to optimize their transmit power and trajectory whilst ensuring they are at a safe distance from one another.

To manage interference, the work in [219] proposes a channel access method for use between UAVs that operate in two modes, namely radar-only and radar-n-communicate. Further, UAVs have a steerable analog antenna array to form multiple beams to minimize interference to non-receiving UAVs. In the case a beam covers multiple receiver UAVs, time and frequency division are used to isolate transmissions. In the time division case, UAVs adopt IEEE 802.11. If there are sufficient number of channels, then each UAV within the same beam will be given a channel as per their packet arrival rate.

The work in [220] focuses on minimizing interference during inter-UAV communications, where communication signals are also used to sense aerial targets. Further, UAVs are divided into small groups to cooperatively detect aerial targets to meet a given CRLB threshold and ensure a minimum communication rate. The main decisions to optimize include (i) the number of UAVs in a group, (ii) a UAV's position, turning angle, and its UAV speed, and (iii) UAV transmit power.

Reference [221] considers how sensing errors impact communication rate. More specifically, the authors of [221] quantify how the sensing errors of a mobile user affect its communication rate, which they call sensing error aware (SEA) communication rate. They then aim to optimize the said SEA communication rate by optimizing a UAV's position, user-UAV association and bandwidth. In addition, they adapt the number of time slots allocated to sensing mobile users, where a higher mobility results in more frequency sensing or number of time slot used for sensing.

Future networks will use neural networks to make sense of an environment. In this respect, reference [222] considers UAVs that use a Deep Neural Network (DNN) for inference. They communicate with users using ISAC signals. They then collect and process echoes using a DNN. A key issue is the cost to offload echoes data to a control UAV for processing. To this end, UAVs split a DNN, where they compute some layers locally, and offload the result to the control station that executes the remaining layers of the DNN. Given this setup, the focus is on maximizing the sum-rate of users. The main decisions include user-UAV association, target-UAV assignment, DNN splitting point, transmit beamforming vector of UAVs, computation resource allocation at UAVs and their location. The main constraints relate to computation and communication latencies, and sensing accuracies.

A challenging case is communicating with mobile users, where works such as [223] consider mobile targets (vehicles) supported by road side units (RSUs) and UAVs. A target/vehicle can only associate to a UAV or a RSU. To maximize the sum rate to targets/vehicles, the proposed solution optimizes the trajectory of UAVs, UAV-target association, and sub-carrier allocation subject to a given performance on sensing accuracy. Another work such as [224] proposed a multi-agent reinforcement learning solution that enables UAVs to learn a policy that optimizes their trajectory, beamforming vector and user-UAV association. In addition, the solution incorporates a periodic K-means method to renew UAV-user associations. In a different work, the UAVs in [225] are either *static* or *mobile*. *Static* UAVs ensure coverage of an entire region, whereas *mobile* UAVs are placed dynamically depending on user density. In particular, they help alleviate the workload of UAVs as each UAV can only service a finite number of users. A key challenge is that targets estimation becomes more complex as compared to *static* UAVs case.

2) *Sensing*: Here, prior works aim to maximize sensing performance. More specifically, reference [226] focuses on posterior CRLB (PCRLB), whereas the work in [227] aims to minimize the maximum CRLB of targets. To maximize the said sensing metric, the UAVs in [226] optimize their transmit power, bandwidth and sub-channel allocation to track

targets and communicate with users. A key consideration is to minimize the interference between the sub-channels used by different UAVs. In [227], the authors consider a bistatic system whereby UAVs are aided by terrestrial base stations that help determine the location of targets. This information is then used by UAVs to localize targets or optimize their trajectory and set their transmit power. Further, the problem in [227] involves selecting base stations to process radar signals, which impacts the sensing CRLB of targets. Both works consider mobile users, and use OFDM for communication and sensing. However, they do not consider communication resources between UAVs, or UAVs and base stations. Lastly, they ensure the data rate of users is above a given value.

3) *Multi-Objectives*: In this section, we discuss works that aim to maximize both communication and sensing performance concurrently. To do that, in reference [228], UAVs optimize their user association, trajectory and transmit power using a centralized and distributed reinforcement learning approach. The work in [229], [230] and [231] also has a similar aim. Both [230] and [231] consider optimizing sensing accuracy of targets as per CRLB, whereas [229] uses mutual information rate. Another difference between these works is that reference [230] considers sub-carrier allocation. Further, the work in [229] models interference from jammers and employ game theory to design a distributed learning algorithm; both [230] and [231] proposed a centralized algorithm.

There are also works that incorporate wireless charging. For example, the users in [232] first harvest energy from radar signals. Specifically, time is divided into downlink and uplink phases. In the downlink phase, UAVs perform radar sensing, which also charges users. In the uplink phase, users transmit their data to a UAV in their allocated time slot. The objective is to maximize the minimum radar SINR and minimum throughput of users. Note, unlike [133], the number of radar sequences is fixed. The optimization problem at hand is to determine radar waveform or sequences, receive filter used to process echoes, total time duration and time allocated for each user, uplink transmit power of users and UAV trajectory. The UAVs in [233] first use their radar signals to charge devices (users) via wireless power transfer for a number of time slots. After that, they schedule devices to transmit to a UAV. The goal is to maximize the minimum sensing SINR at devices and user data rate. The main decision variables include UAV trajectory, transmission waveform, receive filter, transmit power of devices, and the duration of communication and sensing time slots.

Different from the above works, reference [160] considers a bistatic system where UAVs transmit radar signals to sense mobile targets, where the echoes of the said signals are then received and processed by a ground base station. The base station then estimates a mobile target's velocity and location. After that, it optimizes the trajectory of UAVs in order to optimize the sum-rate from UAVs to the mobile target, and also the sensing estimate CRLB of a mobile target's location and velocity estimates.

In a different work, each user/target in [234] must be covered by multiple secondary UAVs. Further, each user/target must receive at least a given amount of data from secondary

UAVs. A separate channel is used for targets detection and communication. The performance metric is a utility that corresponds to the (i) target detection probability of targets, and (ii) amount of data transmitted by secondary UAVs to target(s) and a master UAV. The problem at hand is to determine whether a secondary UAV senses or communicates with a target as well as its trajectory.

Similar to [217], the UAVs in [235] carry contents required by users as well as sense targets. A key issue is grouping users based on similar contents and their location. Further, UAVs must maintain connectivity to a base station to download the required contents. The main performance objective of [235] is to maximize the weighted data rate to users and sensing power at targets; here, the sum data rate corresponds to the total contents delivered to users. The proposed solution optimizes the precoder matrix at UAVs to maximize the said performance object whilst ensuring users receive a minimum data rate and radar sensing performance.

The authors of [236] consider UAVs, emergency vehicles and robot dogs with a camera deployed in a disaster zone. Further, there are base stations that may be destroyed during a disaster, and devices that collect environmental data such as temperature. The collected data is then sent to a UAV or emergency vehicle. UAVs and emergency vehicles also emit radar pulses to detect users and sensing spots. In this respect, the work in [236] aims to compute a policy that optimizes the trajectory of the UAVs, emergency vehicles and robot dogs in order to minimize the average delay attributed to data transmission from devices and sensing.

To date, there are two works that equip UAVs with NOMA, where a key problem is clustering users and assigning each cluster to a UAV. Further, the membership of clusters may change as UAVs or/and users move. In addition, as per the requirement of NOMA, the transmit power of UAVs must be optimized to ensure successful decoding at users. Given the above, reference [237] proposes a reinforcement learning solution to cluster users, and to determine the trajectory and transmit power of UAVs. Using the said solution, the UAVs in [237] aim to minimize the average downlink transmission delays and sensing rate to targets. In contrast, the work in [238] aims to maximize communication and sensing rate. It also considers RIS. The solution in [238] optimizes the following variables in order: UAV positions, UAV-user associations, beamforming vector at UAVs, and UAVs transmit power.

There is only one work that considers computation. Specifically, the UAVs in [21] provide computation service to ground devices, meaning a key decision variable is the computational capacity allocated to devices. Both UAVs and devices sense targets (obstacles). In this respect, devices have to decide whether to offload their data to a UAV after sensing targets. Another issue is fairness, where UAVs must ensure users or areas with more targets are visited more frequently. To this end, the work in [21] presents a reinforcement learning solution to optimize (i) task completion delay, energy consumption of devices, and (ii) ensure the radar information rate of targets is above a given threshold.

E. Others

A number of works aim to minimize the total energy used to carry out communications and sensing tasks. They include [239], [240], [241] and [242]. Briefly, reference [239] aims to minimize the weighted sum of energy incurred by a UAV for communication, sensing and propulsion. Its main decision variables include user scheduling, transmit power and UAV trajectory. The main constraints relate to ensuring the accumulated data from users and sensing rate are above their respective threshold. The work in [240] considers a UAV and an Unmanned Surface Vehicle (USV) that must remain connected at all times. At hovering points, the UAV senses targets and the USV collects environmental data. Between hovering points, i.e., during flight, the UAV communicates with users. The main decision variables relate to the number of hovering points, beamforming vector at the UAV and the trajectory of both vehicles. Reference [241] considers computation, where ground users generate computing tasks that are then offloaded to UAVs; i.e., UAVs have computation tasks in addition to communication and sensing tasks. In this respect, the total energy consumption of UAVs also includes computation.

An interesting work is [242], where it addresses two problems. The first problem involves data or samples collection of targets by UAVs in order to ascertain their location. The goal here is to maximize the Maximum Likelihood Estimation (MLE) of targets using the minimal amount of energy. Further, they store distance measurements to target location mapping in a neural network, which is trained using the federated learning framework. The second problem uses the neural network to retrieve the location of targets, which is then used to minimize the maximum energy used by UAVs to sense targets and transmit to users at a given data rate.

Lastly, the work in [243] considers AoI, where a wireless sensor network is supported by UAVs with a directional antenna. These UAVs detect targets and download data from sensor nodes. The goal is to minimize the average AoI of data from sensor nodes and ensure targets are detected by UAVs with a given probability. The main decision variables include UAV to sensor node association, UAV trajectory, time allocation dedicated to sensing and communication and the antenna beamwidth used by UAVs to detect targets.

F. Observations

The high level goal of all works is to design a solution that allows multiple UAVs to collaboratively carry out communication or/and sensing tasks. To do so, they solve an optimization model centrally to determine the optimal allocation of resources, or propose a distributed solution whereby UAVs allocate resources themselves. As per Table V, we see that the most number of works is in the MUMT category. Similar to the single UAV case, all works mainly optimize along a 2D plane; i.e., UAVs have a fixed altitude. A key issue is collision avoidance where UAVs have to be at a certain distance from each other and targets. This is achieved by having a constraint that limits the distance between UAVs. Most works consider quad-rotor UAVs; only the work in [236] has considered autonomous ground vehicles. Unlike the single

UAV case, assigning user(s) or/and target(s) to a UAV is necessary, where UAVs can only serve a finite number of users. Moreover, sensing accuracy improves with more UAVs as a target can be sensed by multiple UAVs or/and it is more likely to be near a UAV. Apart from that, some users may require specific contents that are only available on a subset of UAVs, which leads to a service placement sub-problem.

To date, only a few works have considered energy, where reference [228] and [244] consider the energy consumed by UAVs, and the solution in [232] considers the energy at users. There is also a lack of works on energy harvesting UAVs or/and users. Most works assume static targets, see Section III-B and [213], [214], [215] for examples. On the other hand, in Section III-A, works such as [186], [187], [188] have used a Kalman filter to track targets. Hence, ensuring CRLB of targets is a key requirement or constraint. In addition, a target can be a user, an obstacle [20], a rogue UAV [209] or an area [190], [192].

Many works have considered UAVs with a different role, see Section III-B. In general, a master UAV is responsible for collecting and processing sensed data from secondary UAVs. Further, a master UAV has a backhaul link to a base station, e.g., [208], [209], [214]. A key issue here is to ensure the backhaul link or link between master and secondary UAVs has sufficient capacity to transmit/receive data. As another example, a UAV in [215] is responsible for jamming eavesdroppers whilst another UAV communicates with users.

A number of works have considered maximizing the transmissions of sensed data to a fusion center, e.g., [20], [192], [234], [193], [197], [214]. In these works, sensing rate and backhaul link capacity from UAVs to the fusion center must be jointly optimized via UAV positioning and transmit power control. Further, to coordinate transmissions over the backhaul link, most works use time division multiplexing or ensure UAVs operate on a distinct subcarrier, e.g., [209]. Some works have used RSMA, e.g., [141], where the transmit power of UAVs must be optimized jointly to facilitate decoding.

To date, only a handful of works have considered fairness in terms of the communication rate of users or sensing rate of targets, where works such as [144], [90], [91], [121] ensure users or/and targets are visited fairly or their respective rate is similar. In terms of targets, a key issue to consider is that multiple UAVs may be monitoring the same target or region, which leads to redundant sensing data [202]. Besides fairness, optimizing secrecy rate is also important, e.g., [215]. To date, no works have considered using multiple UAVs as jammers. Interestingly, there is only one work on RIS, namely [238].

IV. LOOKING AHEAD

Research into ISAC-enabled UAVs is only in its nascent stage. Hence, there is an abundance of opportunities to contribute to this burgeoning area. Below, we outline some possible research directions:

- A key issue in ISAC and ISACC is interference, which is currently addressed using self-interference cancellation methods, orthogonal channels or TDMA. There is a lack of works that aim to derive a link schedule that

TABLE V

A HOLISTIC COMPARISON OF WORKS INVOLVING MULTIPLE UAVS THAT CARRY OUT ISAC OR/AND ISACC. IN THE FIRST ROW, FOR EACH SECTION, WE ALSO INDICATE THE NUMBER OF PAPERS IN EACH SECTION. A FILLED CIRCLE MEANS ALL WORKS HAVE A GIVEN FEATURE.

Features	SUST (6) (Section III.A)	SUMT (15) (Section III.B)	MUST (4) (Section III.C)	MUMT (38) (Section III.D)
2D Trajectory Planning	●	●	●	●
Safe Distance	○	○	●	●
Static User(s)/Target(s)	○	●	●	○
Known User/Target Location	○	●	●	○
Downlink Communications	○	○	●	○
Energy Consumption	○	○	○	○
Fairness	○	○	○	○
Quad-Rotor UAVs	●	●	●	●
Backhaul Link	●	○	●	○

ensures links are activated at least once. Critically, the link schedule must be short to ensure high link capacity. In this respect, one possible direction is to create a multi-transmit or receive (MTR) UAVs network that operates using millimeter waves radios. UAVs can either transmit *or* receive signal (data or echoes). Unlike prior works that only considered communication performance, e.g., [245], [246], the resulting schedule must ensure a given sensing performance, which involves activating sufficient links/beams to sense target(s) frequently. Another interesting direction is to revisit works, e.g., [247], that study the theoretical capacity of a network to also maximize sensing performance.

- Following the previous point, to date, there is limited work on distributed channel access protocols for ISAC systems. This will be critical in multi-UAVs networks and also vehicular networks, see [50], to ensure communication and sensing tasks do not interfere with one another. This is because UAVs may conduct sensing on their own, where they may sense other UAVs to avoid collision as well as ground targets. We also point out that ISAC-capable UAVs that use high frequencies or pencil beams [32] will require a new medium access control protocol. Further, if users/devices require wireless power transfer, then RF-charging aware channel access protocols will be required, see [248] for examples.
- To enhance sensing performance, UAVs must share data, and collaboratively compute collected data [54]; alternatively, they can offload their data to a server, e.g., [165]. In this respect, works such as [249] can be adopted in a multi-UAV ISACC network. However, the work in [249] has only considered a fixed set of servers and topology. To address this limitation, one possible approach is to consider distributed optimization and model predictive control [250] to determine offloading decisions. There is also much synergy between the research on multi-UAVs ISAC and the classic multi-robot task assignment/allocation problem [251]. Hence, both research communities have ample opportunities to leverage the results of one another.
- Sensing as a Service (SaaS) using UAVs has received

considerable interest, whereby they can be deployed or rented in a on-demand manner to carry out task(s), see [252], [5]. Hence, a research question is how to deploy UAV(s) to carry out sensing or/and communication services/tasks? A preliminary work in this direction is [253], where a UAV has tasks requiring different amount of data from targets/users that affect their computation quality. However, this work assumes preloaded tasks and focuses on one UAV. Here we also note that there are many works on service or cache placement to realize drones as a service, e.g., [4]. Hence, a potential research direction is to jointly consider service placement, computation and ISAC, starting from works such as [222], [217], [4].

- A few works have considered a RIS-equipped UAV, e.g., [103], [104], [121], [139]. In this direction, inspired by works such as [254], a possible direction is to consider one or more solar-powered RIS-equipped UAVs that provide ISAC. Another possibility is to consider UAVs supported by energy harvesting charging stations, see [69]. Further, as mentioned earlier, there is a lack of works that consider RIS in multi-UAVs settings. Hence, allocating resources and analyzing the sensing and communication performance in multi-UAVs networks where all UAVs are equipped with STAR-RIS will be interesting.
- To date, there are no works that consider backscattering tags with sensing functions as targets. Doing so would enrich sensing information received by a UAV or base station as tags have sensing functionalities of their own; see [255], [256] for details. Hence, a possible direction is to consider the problem of forming beams to both passive targets, tags and also users; this problem is also related to works that involve RF charging of tags.
- Prior works assume the flight of UAVs is smooth. However, in practice its rotors and propellers cause jittering, which affects channel estimation [257], and a UAV will be affected by wind [258]. To this end, it is interesting to study how more realistic UAV flight models affect ISAC performance. We also point out that all prior works are theoretical in nature, where their focus is on solving an optimization model either via a deterministic

or reinforcement based approach. Hence, an important research direction is to evaluate ISAC on an actual UAV network testbed.

- Recently, moveable antenna [178] has received considerable interests. To date, there is little works that have sought to exploit moveable antennas on the ground or installed on an aerial platform; a recent work is [259]. A related work is [68] where a gimbal is used to re-orient the beams of a UAV to obtain 3D beamforming. Hence, instead of a gimbal, it will be interesting to investigate how moveable antennas can be installed on a UAV, and how it affects its radar cross section when it functions as a rogue UAV.
- As mentioned, prior works, e.g., [193], have considered age of information. Along this direction, future works can consider age of loop [260] or age of actuation [261], which is targeted at systems that require data collection, and computation before actuation. In this respect, one or more UAVs could sense targets, and send sensed data to an aerial or ground node, which carries out computation of sensed data. After that, it can then instruct some UAVs, perhaps with a different set of sensors, to more closely monitor sensed targets. One specific example is the work in [215] whereby a UAV communicates with users and also senses eavesdropper(s) whilst another UAV(s) is responsible for jamming eavesdropper(s). In this respect, age of loop can be used to characterize the responsiveness of the solution in [215]. Apart from that, the bilevel optimization framework, see [262], can be used to allocate resources, where the first level optimizes the resources for sensing or/and computation, and the second level controls UAVs with actuators.

V. CONCLUSION

This paper has reviewed works that used a single or multiple UAVs to conduct sensing of target(s) and communicate with aerial and/or ground users. More specifically, it has expounded their resource allocation problems that involve trajectory planning and beamforming (or transmit power allocation). In the multi-UAVs case, A common constraint is to ensure UAVs operate at a safe distance from one another. In both cases, optimization models may involve a constraint that ensures some minimum performance in terms of communication, e.g., data rate, and sensing performance, e.g., beamforming gain. In multi-UAVs works, it is common for users to be grouped into clusters to balance workload among UAVs, where each cluster is the responsibility of a UAV. Another reason for clustering is to meet the operational requirement of RSMA (or NOMA). In terms of clustering, users may also be grouped according to their channel gain, position, or required contents. Another common feature is that UAVs and base stations employ ULA or UPA, which leads to decision variables involving beamforming vector or precoding matrix.

In both single and multi-UAV works, in terms of sensing, they use radar mutual information rate, or aim to optimize or ensure the estimated position of targets is within a given CRLB. Further, UAV(s) may estimate the location, range or

radial velocity of target(s), where the state of a target is usually represented using an extended Kalman filter. Other common metrics include beamforming pattern errors or the SINR at targets, beamforming gain, and the probability of targets detection. Further, they may require targets to be sensed fairly or within a given time interval. A less common metric is signal-to-clutter-plus-noise ratio. By contrast, for communication, the common metric is the average sum-rate or minimum sum-rate of users; only the work in [98] has considered effective capacity, which also incorporates queuing dynamics. There are also works that aim to balance sensing and communication performance simultaneously.

A key consideration is interference, where sensing and communication signals may interfere. Further, users or/and UAVs may transmit concurrently. To address interference, UAVs/users can be assigned an orthogonal channel. Another common approach is to assign a different time slot to UAVs, users, or/and communication and sensing signals. Only a few works have considered a full-duplex UAV. In general, prior works may simplify their problem by assuming UAVs have been pre-assigned a time slot or orthogonal channel. Otherwise, they would have to solve a sub-carrier or time slot assignment sub-problem. In addition, if time slots are pre-assigned to a UAV or user, then a sub-problem is sizing the time duration for uplink/downlink communications and also sensing of targets. Another approach is to use NOMA or RSMA, which requires a transmitter to set its transmit power according to the channel gain of receivers.

Another burgeoning area is computation, where UAVs may have to process data, perhaps using a neural network. This requires UAVs to optimize their computation resource. Further, the results of their computation may have to be transmitted to users or other UAVs, which require communication resource. In addition, if UAVs operate as part of an edge AI framework, then they will have to consider different neural network configurations depending on their available resources. A key consideration is the total delay due to computation and communication; this delay usually appears as a constraint in optimization problems.

Lastly, it is likely more future works will consider intelligent surfaces, especially in the multi-UAVs case, moveable antennas, and other types of autonomous vehicles. There are also opportunities to leverage extensive research on the classic multi-robots task assignment problem to facilitate collaborative ISAC. Conversely, research communities interested multi-robots coordination will benefit from ISAC research.

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