Intelligent-Reflecting-Surface-Assisted UAV Communications for 6G Networks

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Abstract—In 6th-Generation (6G) mobile networks, Intelligent Reflective Surfaces (IRSs) and Unmanned Aerial Vehicles (UAVs) have emerged as promising technologies to address the coverage difficulties and resource constraints faced by terrestrial networks. UAVs, with their mobility and low costs, offer diverse connectivity options for mobile users and a novel deployment paradigm for 6G networks. However, the limited battery capacity of UAVs, dynamic and unpredictable channel environments, and communication resource constraints result in poor performance of traditional UAV-based networks. IRSs can not only reconstruct the wireless environment in a unique way, but also achieve wireless network relay in a cost-effective manner. Hence, it receives significant attention as a promising solution to solve the above challenges. In this article, we conduct a comprehensive survey on IRS-assisted UAV communications for 6G networks. First, primary issues, key technologies, and application scenarios of IRS-assisted UAV communications for 6G networks are introduced. Then, we put forward specific solutions to the issues of IRS-assisted UAV communications. Finally, we discuss some open issues and future research directions to guide researchers in related fields.

Index Terms—Intelligent reflective surface, unmanned aerial vehicle, secure communicatons, 6G networks.

I. INTRODUCTION

With the continuous evolution of wireless networks, significant progress has been made in 5th-Generation (5G) networks, which are gradually being commercialized in certain regions. To meet the growing demands of networks, researchers are shifting their focus towards 6th-Generation (6G) wireless networks. Compared to 5G, 6G offers significant improvements in terms of rates, capacities, latency, and reliability [1]. Furthermore, 6G networks are expected to support billions of interconnected devices, catering to different requirements of applications such as smart homes and Intelligent Transportation Systems (ITSs) [2]. Meeting network connectivity

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Fortunately, the above-mentioned challenges can be effectively alleviated, since Unmanned Aerial Vehicle (UAV) communication technology continues to become mature. UAVs can be flexibly deployed in areas with dense network equipment, thus relieving the pressure of large-scale access networks on terrestrial networks, especially in scenarios where the density of network devices changes over time, such as vehicularcommunications [4], [5]. Main lobes of traditional groundbased Base Station (BS) antennas face downwards [6], which necessitates the construction of more BSs to achieve widescale network coverage. By changing the flight altitude, it is possible to cover larger ground areas when deploying UAVs as network relay stations or airborne BSs. Moreover, UAVs can be deployed in areas such as oceans and airspace where ground-based BS signals are difficult to reach, providing robust technical support for achieving seamless network coverage. Furthermore, relying on their flexibility, UAVs can easily establish Line-of-Sight (LoS) links, effectively mitigating the high path loss caused by high-frequency communications.

However, UAV-assisted communications still face development bottlenecks. On one hand, UAVs have limited onboard energy, making it challenging to perform long-term communications and complex computational tasks [7]. On the other hand, the reliability of UAV communications is difficult to guarantee, especially in adverse weather conditions, due to wireless environmental factors [8]. It is worth noting that the aforementioned challenges encountered in UAV communications are promising to mitigate through the use of Intelligent Reflective Surface (IRS) technology, further enhancing the development of 6G networks.

A. Overview of IRS-Assisted UAV Communications in 6G Networks

The IRS consists of a large number of passive reflecting elements, each of which can be dynamically controlled in a software-defined manner. By manipulating the phase, amplitude, and propagation direction of incident signals, the IRS achieves precise control and adjustment of the signal, thereby enhancing the transmission quality [9]. In densely populated urban areas, strategically deploying IRSs can facilitate LoS connections between users and BSs. Unlike active relays, the IRS operates by purely reflecting and manipulating incident signals, without additional signal processing, resulting in significantly low energy consumption and even achieving zeropower relaying.

IRS-assisted UAV communications refer to the use of IRSs to enhance wireless communication link quality, thereby improving UAV communication performance. The integration of IRSs and UAVs offers a promising solution to address various challenges in 6G communications. Specifically, on one hand, through strategic placement of IRSs, UAVs can establish communication links with devices in the vicinity of IRSs without the need to fly close to them, thus saving propulsion energy to a certain extent [10]. On the other hand, the IRS possesses the capability to reconstruct the wireless environment, and its passive beamforming can alleviate the interference caused by a large number of devices in UAV networks. In addition, by widening and flattening the threedimensional beams, the coverage range of UAVs can be expanded with the assistance of IRSs [11]. Furthermore, the combination of IRS and UAV can alleviate severe congestion and fading effects in THz and mmWave frequency bands by leveraging the reconstruction capability of the environment and the mobility of UAVs [8]. It is worth noting that the mobility of UAVs enables full-angle reflection, providing new degrees of freedom for IRS design and deployment.

B. Related Surveys

Some surveys have discussed IRSs and UAVs, and can be divided into three categories: specific implementation of IRSs or UAVs in wireless networks [12]–[18], practical applications based on IRSs or UAVs [6], [19]–[26], as well as the combination of IRSs and UAVs [8]–[10].

For the specific implementation of IRSs or UAVs, authors in [12] summarize the channel estimation and practical beamforming methods for imperfect IRS. Authors in [13] investigate the channel design of IRS-assisted wireless networks, while authors in [14] investigate network modeling based on the integration of IRSs and NOMA. Considering the spatiotemporal variability of UAV wireless channels, authors in [15] discuss the wireless channel modeling of UAVs in detail. Authors in [16] summarise key technologies, issues and solutions in UAV networks with the assistance of Machine Learning (ML) and Mobile Edge Computing (MEC). Meanwhile, authors in [17] discuss problems faced by UAV communications in future wireless networks and summarize feasible solutions. In addition, the standardization progress of UAV cellular communications is discussed in [18].

For applications supported by IRSs, authors in [19], [20] discuss the potential of IRS in wireless intelligent networks. Authors in [21] summarize the current research on IRS-enabled ITSs in detail. Furthermore, visible light communications are considered as a crucial component of future communication networks, and its communication tutorial in combination with IRS is discussed in [22]. For the applications

of UAVs, authors in [23] focus on UAV-assisted aerial access networks, while authors in [6], [24] discuss UAV-assisted cellular networks from system design and industry perspectives, respectively. In addition, authors in [25], [26] introduce the application of both UAV-assisted data acquisition systems and ITSs.

Authors in [8]–[10] illustrate the combination of IRSs and UAVs for wireless networks. Specifically, benefits, current progress and development prospects, issues, and potential solutions of IRS-assisted UAV communications are discussed. It is worth noting that studies in [8]–[10] all highlight the benefits of combining IRS and UAV through simulation tests, while there is still a lack of accurate description of the correspondence among technologies, applications and issues.

In summary, we provide a comparison of the above related surveys in Table I. It is obvious that the use of IRSs or UAVs in 6G networks has been discussed from different perspectives, but the specific ways in which IRSs and UAVs are combined in different scenarios have not been clearly pointed out. Moreover, a comprehensive investigation of the technical and practical aspects of using IRSs to assist UAV communications in 6G networks is still lacking.

C. Contributions

In the era of 6G networks, the integration of IRS and UAV communications can complement non-terrestrial networks and drive a comprehensive development of future wireless communications and their applications. To the best of our knowledge, we are the first to provide a survey on IRS-assisted UAV communications for 6G networks by exploring corresponding application scenarios, common key issues, technological support, specific implementations, and research prospects. Specifically, the contributions of this article can be summarized as follows:

- We summarize common key issues, provide a detailed introduction to related technologies, and discuss specific application scenarios of IRS-assisted UAV communications for 6G networks.
- Based on key issues faced by IRS-assisted UAV communications and applications supported in 6G networks, we summarize existing solutions and provide corresponding lessons learned.
- We present challenges and potential research directions for IRS-assisted UAV communications, which can guide future research and exploration in 6G networks.

D. Organization

Fig. 1 illustrates the structure of this article. In Section II, we provide a detailed introduction to common key issues, key technologies and application scenarios in IRS-assisted UAV communication systems. In Section III, we summarize existing solutions to the specific issues presented in Section II, including energy-constrained communications, secure communications, and enhanced communications. Then, some future challenges and open issues are described in Section IV. Finally, we conclude this article in Section V.

Table I: Comparisons of features and contributions among related surveys.

	D.C		Scopes	5						
Categories	Ref.	IRS	UAV	6G	Contributions					
	[12]	\checkmark	×	×	The design of channel estimation and passive beamforming for IRS is reviewed.					
Specific imple- mentation of IRSs or UAVs	[13]	\checkmark	×	×	ML-based solutions, channel and hardware design for IRS are discussed.					
	[14]	\checkmark	×	×	The network modeling based on the integration of IRSs and NOMA is investigated.					
	[15]	×	Measurement schemes and channel characterization for UAV channels are reviewed.							
	[16]	×	\checkmark	×	Key technologies, issues, and solutions in UAV networks with the assistance of ML and MEC are summarized.					
	[17]	×	\checkmark	×	The benefits of combining UAV and wireless networks are discussed.					
	[18]	×	\checkmark	×	The standardization process of UAV communications and the testbed are reviewed.					
	[19]	\checkmark	×	×	Principles, performance evaluation and enabling technologies for IRS-assisted wireless networks are presented.					
	[20]	\checkmark	×	×	The applications of IRSs and performance enhancements in wireless communications are reviewed.					
	[21]	\checkmark	×	\checkmark	The research on IRS-assisted ITSs is summarized for 6G communications.					
	[22]	\checkmark	×	×	A tutorial on IRS-based indoor visible light communications is investigated.					
	[23]	×	\checkmark	\checkmark	UAV-assisted air access networks in 6G networks are investigated.					
Applications based on IRSs or UAVs	[6]	×	\checkmark	\checkmark	The major barriers, design considerations, potential solutions, and the ability of cellular networks to support UAV communications are reviewed.					
	[24]	×	\checkmark	\checkmark	The use cases, requirements, enabling technologies and unresolved issues of UAVs from 5G to 6G are reviewed.					
	[25]	×	\checkmark	×	The development status and future trends of UAV-assisted data acquisition technologies are reviewed.					
	[26]	×	\checkmark	×	The application potential and challenges of UAV-based ITSs are reviewed.					
	[8]	\checkmark	\checkmark	×	The advantages brought by the combination of IRSs and UAVs are summarized.					
Combination of	[10]	\checkmark	\checkmark	×	The application scenarios, design issues and potential solutions for IRS-assisted UAV communications in air-ground integrated wireless networks are summarized.					
IRSs and UAVs	[9]	\checkmark		×	The advantages and potential of IRS-assisted UAV communications are discussed.					
	$\begin{array}{c c} \text{This} & & \\ \text{article} & & \end{array}$		\checkmark		The common problems, key technologies, application scenarios, solutions and open issues faced by IRS-assisted UAV communications in 6G networks are summarized.					

The symbol " $\sqrt{}$ " represents the article satisfies the property, and " \times " represents not.

II. KEY ISSUES, TECHNOLOGIES AND APPLICATIONS OF IRS-ASSISTED UAV COMMUNICATIONS IN 6G NETWORKS

Different application scenarios of IRS-assisted UAV communications require specialized technical support to meet diverse network demands. In this section, we discuss in detail common key issues, key technologies and application scenarios for IRS-assisted UAV communications.

A. Key Issues of IRS-Assisted UAV Communications in 6G Networks

For IRS-assisted UAV communications in 6G networks, different application scenarios often share some common key communication issues. Among them, energy-constrained communications determine the service duration of the system, secure communications ensure the safety and privacy of the system, and enhanced communications aim to improve various performance metrics. We take the above three issues as examples to provide detailed descriptions. 1) Energy-Constrained Communications: In IRS-assisted UAV communications, the issues of energy-constrained communications refer to energy limitations and energy consumption challenges faced during communications. Specifically, energy-constrained communication issues are obvious in both IRS-assisted UAV communication systems and applications supported by the system.

For IRS-assisted UAV communication systems, the limited on-board energy of UAVs severely impacts the service time of UAV networks [27]. Specifically, the onboard energy of UAVs is not only used to maintain their propulsion, but also for signal relaying or transmission as an airborne relay [10], while the former typically consumes more energy than the latter. In order to efficiently utilize the limited service time of UAVs supported by limited energy, the network design has to make a trade-off between the service time of UAVs and other performance metrics such as throughput [28], which has become a major bottleneck limiting the development of UAV communications.

For applications supported by IRS-assisted UAV commu-



Fig. 1: Article structure.

nications, the limited battery capacity of devices affects their normal operation. In general, most IoT devices supported by IRS-assisted UAV communications are powered by on-board batteries. Effective energy replenishment and low-power transmission methods are crucial to ensure the long-term stability of IoT devices [29], [30]. Simultaneous Wireless Information and Power Transfer (SWIPT) is one effective means of energy supplementation. However, the significant energy consumption associated with long-distance transmission limits the use of SWIPT. Furthermore, network devices supported by IRSassisted UAV communications in remote areas face increasing challenges for low-power transmissions due to the complexity of wireless environments.

Consequently, solving the problem of energy constraints faces many challenges in IRS-assisted UAV communication systems, due to the following reasons:

- Complex wireless environments: UAVs usually work in complex wireless environments, such as high-speed mobile scenarios of Vehicle-to-Everything (V2X) communications and high-altitude scenarios of Space-Air-Ground Integrated Networks (SAGIN) accompanied by various transmission fading. This poses various challenges to signal and energy transmissions of UAVs. In addition, the IRS often needs to be adjusted in a timely manner with changes in the environment to assist UAV communications, which increases the difficulty of system design.
- Multiple factors to balance: Energy issues are the result of multiple factors, including UAV flight trajectories, resource allocation strategies, environmental impact factors, IRS design, transmission beams, and the number of served users. Since these factors need to be comprehensively considered, the complexity of the problem increases greatly, and even NP-hard problem.
- Difficulties in technology fusion: To effectively alleviate

the problem of limited energy, it is often necessary to integrate other technologies (such as SWIPT and Backscatter Communication (BackCom)) into the framework of IRS-assisted UAV communications, which brings new problems. For example, when using SWIPT technology, energy collection and information transmission are conflicted with each other [29]. In addition, in the BackCom scenario, the trade off between energy collection and signal reflection is also important [31].

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2) Secure Communications: In the context of IRS-assisted UAV communications, security concerns primarily involve two aspects: ensuring the integrity of transmitted data and maintaining the confidentiality of communication contents. The former aims to prevent data tampering, damage or loss, while the latter focuses on preventing information leakage. Based on different security concerns, common security threats in IRS-assisted UAV communications can be classified into two categories: malicious jamming and eavesdropping attacks.

Malicious jamming aims to disrupt, compromise, or undermine the performance and reliability of communication systems, which is one of the most easily achievable attacks in IRS-assisted UAV communications. It does not require much information about the target user, but rather interferes with and floods data towards the target user with a malicious jamming device, thereby increasing channel burden and reducing the performance of communication systems [32].

The eavesdropping attack is a traditional network one that illegally acquires network data, leading to information leakage. Eavesdropping attacks can be active or passive [33]. In the passive eavesdropping attack, the eavesdropper does not take any actions other than potentially obtaining the transmitted information, thus not blocking the legitimate user's information reception. Active eavesdropping is an attack that introduces malicious jamming based on passive eavesdropping. Active eavesdroppers use malicious jamming devices to send jamming signals to the target channel, which are typically disguised as indistinguishable natural noise. Therefore, the sending end usually increases the transmission power to maintain system transmission performance [34]. Moreover, the eavesdropper can move to the optimal position for eavesdropping, making it easy to obtain the transmitted information and seriously affecting the quality of signal reception for legitimate users.

There are four reasons that make it challenging to address security issues in IRS-assisted UAV communications:

- Attacks are not easily detectable: In cases where jamming causes signal reception failure, it is merely perceived as regular information loss. Any protocols and strategies above the physical layer are unaware of this, let alone respond to the jamming.
- Difficulties in accurately obtaining attackers' Channel State Information (CSI) and location information: Acquiring accurate information about attackers' CSI and locations forms the basis for effective defense against attacks. However, due to the random nature of attackers' unauthorized access, obtaining accurate location and CSI is rather challenging in wireless environments [35], [36].
- UAV's dynamic mobility: UAVs are typically in a state of motion, and the topology and signal characteristics of their communication links may continuously change. Therefore, security defense strategies need to adapt and respond to the dynamic communication environment in real time.
- Limited energy and computational capabilities: Battery capacities and computational capabilities of participants in IRS-assisted UAV communications are generally limited, making them helpless against attacks with sufficient computing capability [37].

3) Enhanced Communications: In IRS-assisted UAV communications, enhanced communications refer to enhancing the quality and reliability of the communication link through IRS and UAV based technologies. Although the combination of IRSs and UAVs provides possibilities for flexible deployment of wireless networks, achieving fast network rates, large network coverage, short network latency, high spectrum utilization and reliability still faces multiple challenges. These challenges include difficulties of interference management, spectrum resource shortage, challenges of IRS and UAV deployments, complexity of wireless environments, and nonconvexity of multivariate coupling.

a) Difficulties of interference management: The mobility of UAVs results in UAV communication systems vulnerable to unpredictable signal interferences, including interference from broadcast signals, signal congestion caused by simultaneous communications among multiple users, and unintentional interference from other devices. Unlike jamming attacks, this unpredictable interference does not lead to information leakage, but it seriously affects the signal transmission quality. Although IRSs can avoid some of the signal interference by directional beamforming, coordinating beamforming and power control strategies to mitigate interference becomes a complex task for dense-user scenarios. b) Shortage of spectrum resources: The spectrum resource shortage problem arises along with the proliferation of network devices. In IRS-assisted UAV communications, existing Radio Frequency (RF) spectrum designs mainly focus on terrestrial networks, and only a small amount of spectrum is used for airborne networks such as military, satellite communications, and so on. Since the mobility of UAVs leads to dynamic changes in network topology and wireless channel conditions, if these spectrum design and management strategies are directly applied to dynamic airborne UAV communications, the results are poor. Although some articles [38]–[41] have proposed to use frequency bands such as mmWave and THz for communications to alleviate the spectrum shortage, the impact of path loss on the system caused by ultra-high frequency cannot be ignored.

c) Challenges of IRS and UAV deployments: The deployment location of IRSs and trajectories of UAVs need to consider the balance between performance and economy. On the one hand, IRS and UAV deployments should cover the specific service areas as evenly as possible to avoid signal strength deficiencies and signal blind spots. On the other hand, economic effects and deployment overhead minimization should be taken into account for IRS and UAV deployments. Particularly, in scenarios with dynamically changing communication requirements, flexible algorithms for real-time adjustment and optimization should be considered for IRS and UAVs [5].

d) The complexity of wireless environments: Due to the difficulty of CSI acquisition of IRSs, inevitable errors often occur when estimating the channel state of IRSs and UAVs. In addition, the dynamic wireless environment increases the difficulty of channel estimation, and the reflected link of IRSs may lead to spatially correlated frequency-selective fading channels, increasing the design difficulty of UAV trajectories [42]. Especially for air-to-ground communication scenarios, UAV jitter should be carefully treated [5], [9]. In conclusion, challenges posed by the complexity of wireless environments should be addressed in conjunction with the environment itself and system devices.

e) Nonconvexity of multivariate coupling: In order to improve the performance of IRS-assisted UAV communication systems, the joint design of multiple variables is usually required, including UAV trajectories, IRS phase shifts, BS transmit power allocations, and channel assignments. However, these variables, such as UAV trajectories and beamforming of IRSs, the decoding order of Non-Orthogonal Multiple Access (NOMA) and association results between IRSs and users are often coupled [43], [44], resulting in difficulties of problem solving with the characteristic of non-convexity. Therefore, how to design a reasonable algorithm for the non-convex problem is the key to enhance communications.

In IRS-assisted UAV communications, the main challenge to realize enhanced communications arises from comprehensive consideration of the aforementioned issues in the system design. Furthermore, realistic conditions, such as non-ideal channel conditions and UAV jitter, need to be taken into account.

B. Technologies of IRS-Assisted UAV Communications in 6G Networks

In order to improve the performance of IRS-assisted UAV communications, specific technologies, including channel estimation, beamforming, resource allocation, and trajectory optimization, are employed. These technologies play different roles in facing the issues presented in Section II.A. For example, channel estimation and beamforming can alleviate the complexity of wireless environments [35], [36], [45]–[50], and resource optimization plays an important role in energy-constrained communications [29], [30], [45], [46], [51]–[54], secure communications [34], [38], [48], [55]–[57], and enhanced communications [39], [40], [42]–[44], [58]–[64]. Trajectory optimization can reduce the risk of being attacked and the cost of deployment [34], [35], [38], [41], [49], [50], [55], [57], [65]–[67] to some extent. In the following, we provide a detailed description of these technologies.

1) Channel Estimation for IRS-Assisted UAV Communications: Channel estimation refers to the estimation and inference of channel characteristics based on the received signal in wireless communication systems, in order to correctly process and decode signals at the receiving end. In general, the key to channel estimation lies in the acquisition of CSI. In other words, channel estimation in tends to obtain a complete and accurate channel state based on the limited CSI. In IRS-assisted UAV communications, the challenge of channel estimation comes from three aspects: First, for wireless environments, the wireless channel is complex in nature, and the signal propagation is often affected by various kinds of interference and fading. Second, for UAVs, channel estimation needs to have a strong adaptive nature. Because UAVs are with mobilities and thus cause wireless channel switching, UAV locations and environmental characteristics play a crucial role in determining the primary channel quality [15]. Finally, for IRSs, the number of reflective elements is proportional to the number of channel coefficients [68]. The huge number of channel coefficients may cause a huge estimation overhead. In addition, the IRS lacks signal processing capabilities and traditional channel estimation methods are not fully applicable [69].

In order to improve the performance of channel estimation in IRS-assisted UAV communications, many methods are proposed, mainly including Compressive Sensing (CS)-based channel estimation, cascade-based channel estimation, anchorassisted channel estimation, meta-learning-based channel estimation, Deep Learning (DL)-based channel estimation, and tensor decomposition-based channel estimation. Each method is introduced in the following content.

a) CS-based channel estimation: It is commonly utilized for IRSs and UAVs, and can be integrated with other channel estimation techniques for performance improvement [70]. The basic idea of this method is to leverage the high sparsity of the wireless channel by extracting a sparse representation of the channel from a limited set of measurement data, to achieve the recovery of the complete CSI. This method can also use a few pilot signals to obtain relatively accurate CSI, which greatly reduces the training overhead of channel estimation while effectively estimating channel parameters [71], [72].

b) Cascade-based channel estimation: It is suitable for scenarios with multi-level channels and multiple users. This method exploits the correlation property of channel cascading, i.e., the cascaded channel coefficients are scaled versions of the superimposed lower-dimensional CSI of the specific channel [68], [73], thus significantly reducing the training overhead of channel estimation. For multi-user scenarios, the channel of any single user is also a low-dimensional scaled version of other channels, thus allowing effective estimation of all channels with a low overhead on the BS [73].

c) Anchor-assisted channel estimation: It is mainly applicable to scenarios with a large number of fully passive IRS reflective elements and users. The method first allows anchor nodes to be deployed near the IRS to obtain partial CSI through anchor-assisted training and feedback. The information is then used to efficiently estimate the cascaded channels between BS and IRS with additional training by the user [74]. Thus, with the assistance of anchor nodes, the method can reduce the huge training overhead incurred by signal transmission and reception, due to the increasing number of users and IRS reflection elements.

d) Meta-learning-based channel estimation: The idea of meta-learning can be simply understood as "learning to learn". It usually contains two layers of meanings: one is to enable machines to gain experience in tasks and improve their ability to complete tasks, and the other is to expand the capabilities of machines to adapt to similar tasks [75]. The channel estimation based on meta-learning mainly solves the problem of inaccurate channel estimation when the network environment changes and the generalization ability is poor. In addition, the introduction of convolutional layers can also improve the generalization ability of channel estimation.

e) DL-based channel estimation: DL-based channel estimation is suitable for highly complex dynamic channel environments with high-dimensional spatial features and nonlinear channel characteristics. Its main idea is to use DL methods, such as neural networks, to analyze and process received signals and obtain CSI. Recurrent Neural Networks (RNNs) and Convolutional Neural Networks (CNNs) are commonly used methods in DL. RNNs can capture the temporal dependencies in sequential data, allowing them to estimate the current channel based on previous channel samples, and is therefore commonly used for continuous-flight UAV channel estimation [76]. Long Short-Term Memory (LSTM) is a special RNN algorithm that overcomes the gradient vanishing and gradient explosion problems of traditional RNNs when dealing with long sequences. Through the gating mechanism and the memory unit, LSTM can capture the long-term dependency of the channel, so as to track the channel and realize dynamic channel estimation [77], [78].

CNNs can autonomously learn feature representations suitable for channel characteristics. With their deep structures, weight sharing, and parallel computing capabilities, CNNs can reduce the algorithm complexity of channel estimation for a large number of IRS reflection units, while ensuring estimation accuracy [79], [80]. In addition, the offset learning in DL can simulate dynamic channel states [80], and deep residual learning provides a method for recovering channel coefficients from the noise-based pilot observation data [79].

f) Tensor decomposition-based channel estimation: It is mainly applied in large-scale antenna scenarios with multiple inputs and multiple outputs. The tensor-based channel estimation technology describes the spatio-temporal characteristics of the channel by constructing a channel tensor model, and then uses mathematical methods such as tensor decomposition to process and optimize the channel tensor to estimate CSI. This method can capture the high-order relationships and spatial correlations of the channel, thus improving the accuracy and efficiency of channel estimation. In addition, tensor-based channel estimation can also exploit channel sparsity to further improve its performance [81].

2) Beamforming for IRS-Assisted UAV Communications: Beamforming refers to adjust the radiation direction and signal gain of a beam by controlling the phase shift and weight of antenna elements (such as IRSs) to form different radiation patterns [82]. In essence, beamforming is a spatial filtering method, which is initially used for specific directional radiation or energy acquisition. In IRS-assisted UAV communication systems, beamforming technology plays a significant role in improving system performance [83], [84] and ensuring system security [55], [65].

In IRS-assisted UAV communications, if communication takes place when the UAV is moving at a high speed, beam tracking design during the beamforming process is needed to adapt the directional beams to the UAV's movement. This is not necessary in static UAV scenarios. Therefore, beamforming can be further categorized into static beamforming and beam tracking (dynamic beamforming).

a) Static beamforming: Its critical design challenge is the trade-off between the overhead of acquiring instantaneous CSI and the performance of beamforming. In fact, the effectiveness of beamforming largely depends on the accuracy of CSI, where better beamforming results are achieved with more accurate CSI. However, there is currently no mature method to obtain precise instantaneous CSI for IRSs [85]-[87]. Therefore, most beamforming designs for IRSs are based on statistical/mixed CSI [88], using statistical CSI of IRSs as a substitute for part of the instantaneous IRS to balance the channel estimation overhead and beamforming performance. It is worth noting that for scenarios where there is no instantaneous CSI of IRSs available, beamforming can be realized by techniques such as DL, beam training, channel tracking, and heuristic algorithms [12]. The beamforming for hybrid CSI and non-explicit CSI is described below.

• Beamforming with hybrid CSI: It is a beamforming approach by reasonably weighing and combining statistical CSI and instantaneous CSI. Statistical CSI changes slowly and only statistical characteristics of the channel are needed to know, and thus it is easily obtainable compared to instantaneous CSI. Therefore, this method has the advantage of low overhead. A common channel estimation method for hybrid CSI is the dual time-scale based hybrid CSI beamforming [85]. Specifically, the phase shift of the passive IRS is first optimized by statistical CSI, and then the transmit beamforming of the

access point is optimized to cater to the instantaneous CSI of the user's effective fading channel.

Beamforming without explicit CSI: This is a beamform-• ing method that does not require any instantaneous CSI. Beam training is one of the common methods, which achieves the best result for the system by selecting the best beam from a predefined beam set. However, beam training tends to incur a significant overhead, and authors in [86], [89] propose hierarchical and random training beamforming methods to further reduce the beam training overhead. DL-based beamforming is another beamforming method without instantaneous CSI, which learns the mapping relationship between channel characteristics and beamforming from training data to achieve intelligent beamforming [87]. In addition, Reinforcement Learning (RL) can also be used for beamforming design. In this method, the system is described as an intelligent body, which optimizes the global behavioral strategy to select the optimal beamforming parameters for beamforming based on the current state and the received reward [48].

b) Beam tracking: For dynamic beamforming, fastchanging channels and hardware/resource limitations hinder the implementation of beam tracking. In addition, the time overhead of beam tracking implementation should be taken seriously in scenarios with real-time requirements. To solve the above challenges, filter-based beam tracking and learningbased beam tracking are proposed.

- Filter-based beam tracking: Its main idea is to continuously adjust the coefficients of the filter in real-time based on feedback information, to adapt to channel variations and achieve beam tracking. Due to the simplicity of the filter update process and clear target orientation, it can enhance signals in specific target directions. Therefore, it is suitable for scenarios with relatively dynamic environments and time-critical requirements. It is worth noting that the utilization of single-pulse signals in designing filter-based beam tracking methods can address the high nonlinearity problem of codebook-based beam tracking models and significantly reduce the overhead of beam scanning [90]. Moreover, the distributed beam tracking approach with multi-anchor node collaboration is suitable for scenarios where environmental factors have a significant impact on beam tracking [91].
- Learning-based beam tracking: It utilizes ML technologies such as DL, to train models and learn beam tracking strategies. This approach exhibits strong adaptability to environmental changes and has powerful generalization capabilities, but may not be suitable for scenarios with limited computational resources. Among them, Q-learning can be used for beamforming design based on current and past observation data, striking a balance between data acquisition and beam tracking costs [92]. Additionally, LSTM can leverage the temporal correlation of beams to model the channel, making decisions in adjusting the beam direction [93].

In general, the selection of beamforming methods is different according to different scenarios. In order to obtain a good beamforming effect, the combination of multiple methods is a good choice [94]. Additionally, beamforming is needed to jointly considered with channel estimation to ensure the coordination between beamforming performance and channel CSI acquisition overhead.

3) Resource Allocation for IRS-Assisted UAV Communications: For IRS-assisted UAV communications in 6G networks, the limited transmission bandwidth, UAV energy, and transmission power restrict the system performance. To fully utilize the limited network resources, e.g., power [42], [54], [58], bandwidth [42], [95], IRS reflection units [42], [60], and computing resources [39], [53], efficient resource allocation strategies should be designed. By uniformly managing and allocating resources in the communication system, various performance metrics can be improved, including system delay [39], system energy consumption [54], network rates [43], and spectrum utilization [44].

It is common to follow certain principles for resource allocation. The multi-level water-filling principle aims to maximize the overall system performance, e.g., total network rates, by allocating communication resources to each channel, and then gradually reducing the allocated resources for each channel based on the quality of wireless channel conditions [42]. However, this allocation principle requires the accurate acquisition of user channel information, which may increase the system overhead and require complex control algorithms to ensure appropriate resource allocation. In the system design, resource allocation is not strictly based on the multi-level water-filling principle; instead, practical design requirements are taken into consideration. For example, authors in [42] consider peruser heterogeneous quality-of-service requirements. Authors in [96] consider dynamic resource scheduling. Authors in [46] consider constraints on individual data rate requirements and the maximum tolerable outage probability. Another common resource allocation strategy is the priority-based allocation, where users with higher priority or specific needs are allocated with more resources. This allocation principle is widely used in the spectrum allocation process of Cognitive Radio (CR) systems, ensuring spectrum resources for Primary Users (PUs) first and then Secondary Users (SUs) [64], [97].

In IRS-assisted UAV communication systems, resource allocation is usually formulated as optimization problems, and the corresponding algorithms include game theory, DL, heuristic, and approximation algorithms, which are described separately below.

a) Game theory-based resource allocation: The basic idea of this method is to establish a game model that considers both competitions and cooperations among users, making resource allocation decisions based on game strategies to balance the interests of different users and achieve optimization goals [98]–[100]. However, for large-scale systems, the complexity of game models is significant.

b) DL-based resource allocation: Its basic idea is to train neural networks to learn patterns and rules of resource allocations to adapt to different scenarios and data, enabling intelligent resource allocation decisions [59], [98]. However, this method has certain requirements for the amount of training data and training time. *c)* Heuristic algorithm-based resource allocation: It can efficiently obtain approximate solutions for resource allocation problems, but without guaranteeing the quality of the obtained solutions. It simulates the human heuristic thinking process by introducing a series of heuristic rules, strategies, and methods to search the solution space. Common heuristic algorithms include simulated annealing algorithms, genetic algorithms, and Particle Swarm Optimization (PSO) algorithms [101].

d) Approximation algorithm-based resource allocation: Its basic idea is to find a near optimal solution or a solution that satisfies specific conditions within an acceptable time frame [58]. Although an acceptable solution can be obtained, this method often sacrifices a certain level of accuracy to reduce computational complexity, and the obtained solution cannot guarantee global optimality. Common approximation algorithms include greedy algorithms, SemiDefinite Relaxation (SDR) algorithms [102], and Successive Convex Approximation (SCA) algorithms [46].

4) Trajectory Optimization for IRS-Assisted UAV Communications: In IRS-assisted UAV communications, trajectory optimization refers to the specific design of the UAV's movement trajectory to improve the system performance. The UAV's trajectory and position can greatly affect performance metrics such as communication delay, coverage ranges, power consumption, and system throughput. It is worth noting that the height of the UAV is critical for LoS link establishment. Although authors in [40] discuss performance improvement brought by trajectory optimization, they simplify the UAV's three-dimensional trajectories and positions to a two-dimensional plane, ignoring the impact of height on the system. In addition, IRSs can enhance the flexibility of UAV trajectories. For instance, in scenarios with multiple Ground Users (GUs), UAVs no longer need to alter their original trajectories to maintain the minimum distance from all users. Instead, by intelligently deploying IRSs near GUs, the system can satisfy users' connectivity requirements without consuming excessive time and energy.

Similar to resource allocation, trajectory optimization is often formulated as an optimization problem in IRS-assisted UAV communication systems. The process of trajectory optimization is complicated. On the one hand, optimization variables are diverse, including positions, velocities, and flight angles of UAVs, while there are mutual constraints and interactions among these variables. On the other hand, when multi-user or wide-service-range scenarios are involved, the trajectory optimization becomes much complicated and the computational complexity of the solution is very high. Therefore, efficient trajectory optimization algorithms are necessary. Generally, some algorithm, such as greedy algorithm, PSO, DL, and RL can be used for trajectory design, which are described in detail below.

a) Trajectory optimization based on greedy algorithms: It tries to construct the UAV trajectory based on the current optimal choice (such as the shortest flying distance, strongest signal, and minimum interference) to achieve a local optimum [103]. The greedy algorithm has low complexity and is commonly used for simple and real-time trajectory optimization UAV communication scenarios. However, its main drawbacks are the lack of backtracking abilities, tendency to reach local optima, and sensitivity to initial conditions.

b) Trajectory optimization based on PSO: It optimizes the UAV trajectory by simulating the movement of a particle swarm in the search space. Each particle can simultaneously update its velocity and position to facilitate the search for the optimal solution, thus approaching the global optimization [104]. This algorithm also has low complexity and is suitable for complex trajectory optimization scenarios that require timeliness.

c) Trajectory optimization based on imitation learning: It is a trajectory optimization approach that learns and optimizes its own flight path by imitating the trajectories of experts or other UAVs. This method exhibits pronounced effectiveness in intricate environmental flights and multi-UAV collaborative tasks [105]. However, its effect is profoundly contingent upon high-quality training datasets, with potential limitations in generalization when encountered with novel scenarios.

d) Trajectory optimization based on DL: This method utilizes DL models to learn the optimal UAV flight trajectory. By inputting the state information of the UAV and the communication environment, DL model can learn the mapping relationship between the trajectory performance and the state, and output the optimal trajectory [106]. Trajectory optimization based on DL exhibits strong applicability and high accuracy, and is used to solve complex nonlinear trajectory optimization problems in large-scale communication environments. However, the demand for large amounts of tagged data restricts its effectiveness for trajectory optimization.

e) Trajectory optimization based on RL: By establishing an interaction model between the intelligent agent and the environment, the agent learns the optimal action strategy through continuous trials to maximize cumulative rewards such as Energy Efficiency (EE), which is the ratio of transmission rates to system energy consumption [59]. The greatest advantage of this method is robust environmental adaptability without precise prior data [107]. Consequently, it is widely used in UAV trajectory optimization scenarios with multiple objectives and complex dynamic environments. However, the elevated computational complexity demands additional computational resources and time, particularly for trajectory optimization of multiple users in complex environments.

C. Applications of IRS-Assisted UAV Communications in 6G Networks

IRS-assisted UAV communications play an important role in many scenarios, mainly including SAGIN, V2X communications and large-scale IoT. In this subsection, we detail benefits that IRSs and UAVs bring to the system through three examples. A schematic of the three scenarios is depicted in Fig. 2.

1) **IRS-Assisted UAV Communications for SAGINs:** The SAGIN refers to the integration of ground networks with aerial and space networks, providing global coverage and supporting communications for heterogeneous networks [108]. This seamless coverage network provided by SAGINs plays a significant role in remote areas, maritime communications,

post-disaster communications, and other fields. The SAGIN can be divided into three layers: space, air, and ground, which fully integrate communication resources of the three layers to leverage the advantages of heterogeneous networks [109]. The air layer mainly refers to high altitude platforms composed of UAVs, balloons, airships, and other equipment, which can enhance their communication performance through the mobility of the air platform. However, unlike ground networks, limited computational capabilities and battery capacities of high-altitude platform equipments [108], [108], as well as the security of air-to-ground communications [110], can severely hinder the development of non-terrestrial networks. Therefore, the implementation of non-terrestrial networks is more challenging than ground networks.

IRSs and UAVs play significant roles in SAGINs. As shown in Fig. 2b, UAVs can be flexibly deployed in ocean, desert, and dense urban scenes, providing a wide communication coverage. At the same time, IRSs, in coordination with UAVs, reflect signals to obstructed areas, further enhancing network coverage [111]. Additionally, flexible deployments of IRSs and UAVs enable SAGINs to have high adaptability, especially deploying IRSs on UAVs [112]. Specifically, IRSs and UAVs play different roles in various network layers of SAGINs.

- Air-to-air networks: The combination of IRSs and UAVs brings increased mobility to the air-to-air network. IRSs and UAVs can be deployed to facilitate dynamic responsiveness to environmental and mission requirements through information sharing and collaborative deployment strategies. Furthermore, IRSs and UAVs enhance the robustness of air-to-air networks, allowing them to autonomously maintain critical communications when signal interruptions occur.
- Air-to-ground networks: In the air-to-ground network, the combination of IRSs and UAVs can improve ground transmission and emergency response capabilities by establishing flexible and efficient LoS communication links [109]. For example, in emergency rescue and disaster relief situations, IRSs can be used to assist UAV communications, achieving quick response and information transmission.
- Satellite networks: On one hand, IRSs can enhance satellite signal coverage and transmission quality by optimizing signal transmission paths. On the other hand, UAVs are used as flexible mobile relay nodes that can be rapidly deployed to areas where enhanced satellite signals are required [113]. This combination enhances the availability and reliability of satellite networks, particularly in remote or signal-constrained regions.

2) IRS-Assisted UAV Communications for V2X Communications: V2X refers to the communication and interaction between vehicles and various entities in the surrounding environment. It mainly includes Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) [5]. It is a technology based on the Internet of vehicles and ITSs, aiming to improve vehicle safety, efficiency, and convenience. The implementation of V2X communications is required to handle the real-





Fig. 2: Application scenarios for IRS-assisted UAV communications: (a) IRS-assisted UAV communications for V2X; (b) IRS-assisted UAV communications for SAGINs; and (c) IRS-assisted UAV communications for large-scale IoT.

time movement of vehicles and the huge network demand [114], [115]. For the real-time mobility of vehicles, a series of problems including network topology transformation, and wireless access switching arise. Concurrently, high-quality links, imperceptible latency, and secure transmission are also demanded by V2X communications.

Introducing IRSs and UAVs into V2X networks can improve network transmission quality. A fixed IRS can only enhance communications for nearby vehicles. As shown in Fig. 2a, with the flexibility of UAVs, IRS-assisted UAV communications can adapt well to the rapid movement of vehicles. On the one hand, UAVs can be dynamically deployed with vehicles to adapt to terrestrial network transmission pressure under different vehicle densities. Especially in densely populated urban scenes, the road vehicle density always changes over time and area, and dynamic UAV deployment can not only improve network service quality but also reduce unnecessary network costs to a certain extent. On the other hand, aerial IRSs can establish LoS links with vehicles flexibly [5]. Reliable communication links are an important guarantee for vehicle communications and passenger safety, especially for highquality wireless transmission applications such as autonomous driving. In V2X networks, IRS-assisted UAV communications can be utilized to improve the following metrics:

- Communication distances and network coverage: Generally speaking, V2X networks require long communication distances and large network coverage ranges. UAVs can achieve this by high-altitude hovering or specific trajectory planning. In addition, placing the IRS at suitable locations to reflect and enhance signals in areas obscured by buildings, further expanding communication distances and coverage range [115].
- Communication quality and network rates: V2X networks require high-rate and low-latency communications

to meet real-time communication requirements among vehicles. By using IRSs to optimize and enhance signals, the effects of channel fading and multipath interference on signals can be reduced, improving signal transmission quality and network rates of V2X networks [114]. Furthermore, UAVs equipped with IRSs can also be flexibly deployed, further reducing the risk of signal obstruction.

Communication security and privacy protection: V2X networks need to support secure and reliable communications to ensure privacy protection and safety of vehicles and drivers [115]. IRS beamforming technology can be utilized to enhance the communication quality of legitimate links and attenuate that of unauthorized links, thus fortifying security and confidentiality of communication signals [5]. Furthermore, judiciously planning UAV trajectories to distance them from attackers can further mitigate the risk of communication link attacks [116].

3) IRS-Assisted UAV Communications for Large-Scale IoT: The IoT is a system that connects a wide range of intelligent digital devices with sensing and computing capabilities, widely used in urban construction, smart agriculture, healthcare, and home automation [59]. However, with the continuous development of the IoT network, the shortcomings of traditional networks are gradually being exposed. First, the large number of IoT connections increases the burden on the network. On the one hand, numerous network connections exacerbate spectrum scarcity. On the other hand, the wide distribution of devices requires an innovative way to overcome the path loss associated with long-distance transmission and achieve ubiquitous network coverage [98]. Second, the shortage of energy for IoT devices limits the development of IoT. How to extend the lifespan of IoT devices in a cost-effective way needs to be considered. Finally, the security of IoT networks is crucial. The interconnectivity of IoT devices and

their physical environment also introduce new attack surfaces that require accurate and predictable adaptivity to ensure security [117]. In addition, IoT security not only determine the smooth operation of the IoT network, but also pose the risk of zombie networks threatening the entire wireless network ecosystem [118].

As illustrated in Fig. 2c, IRSs and UAVs can establish connections with IoT devices flexibly and realize large-scale network coverage. This helps IoT networks to realize large-scale network accesses, high-quality transmission, prolonged IoT device lifetime and secure communications, which is described in detail next.

- Large-scale network accesses: Spectrum shortage and multi-user interferencemobility management are the most significant difficulties to realize large-scale network accesses for IoT devices. On the one hand, by designing the deployment location and reflection coefficient of IRSs, the channel differences among different users can be enlarged, to distinguish the channels of different users easily, thus enhancing the NOMA system gains. Moreover, IRSs can reconfigure channel conditions, and thus the decoding order of users can be changed according to the demands of quality of service [119]. On the other hand, IRSs can directionally control the reflection direction of the incident signal, thus reducing the interference of different signals among multiple users.
- High-quality transmission: IoT devices are usually widely distributed on the ground, which can cause huge cost overhead if cellular networks are utilized to collect IoT data [59]. IRSs and UAVs can provide network coverage for a designated area in a cost-effective way. Meanwhile, with the beamforming of IRSs and the mobility of UAVs, reliable LoS links can be established with ground nodes, thus improving transmission quality.
- Prolonged IoT device lifetime: IRSs and UAVs can prolong the lifetime of IoT devices from two perspectives: First, the combination of IRSs and UAVs can achieve low-power communications by specific optimisations including UAV trajectories, IRS deployment locations and beamforming, which extends the lifetime of IoT devices from the perspective of energy consumption. Second, IRSs and UAVs can improve the performance of wireless energy transfer. IRS-based passive relaying and beamforming can effectively reduce the energy loss caused by long-distance energy transmission, while UAVs can fly near the ground nodes to reduce the energy transmission distance, which extends the lifetime of IoT devices from a sustainable perspective.
- Secure communications: The security of IoT networks can be enhanced from the physical layer through the use of IRS beamforming to reconfigure the wireless channel and the design of trajectories for UAVs. In addition, UAVs can generate artificial noise to assist in the joint optimization of IRS beamforming design, effectively countering illegal eavesdropping.



Fig. 3: Schematics of BackCom in IRS-assisted UAV communications.

III. SOLUTIONS OF IRS-ASSISTED UAV COMMUNICATIONS IN 6G NETWORKS

In this section, we provide a detailed description of solutions to the related issues summarized in Section II.A, including energy-constrained communications, secure communications, and enhanced communications.

A. Solutions for Energy-Constrained Communications

In IRS-assisted UAV communications, energy-constrained communications can be solved not only from the perspective of reducing system energy consumption, but also from a sustainable perspective based on wireless power transfer. The following are examples of SWIPT, BackCom and other methods to illustrate solutions for energy-constrained communications in detail. Table II provides a corresponding summary of these solutions.¹

1) BackCom for Energy-Constrained Communications: BackCom is a reflection-based wireless communication technology. Devices using BackCom can not only transmit information by designing the impedance matching state in the antenna, but also obtain energy from the RF signal to maintain normal operation, realizing a green communication paradigm [123]. The simplest single-base BackCom system consists of a Backscatter Device (BD) and a reader, where the reader includes a power beacon and a backscatter receiver. During communication, the RF source generates an RF signal to activate the tag, and the backscatter transmitter loads the sent information into the RF signal and reflects the modulated signal to the backscatter receiver [124].

In IRS-assisted UAV communications, using BackCom can reduce system energy consumption while satisfying system requirements for communication performance. Fig. 3 illustrates the communication principle of BackCom. In the BackCom system, the UAV acts as airborne power beacon, providing RF signals to specific areas of the IRS through carefully designed UAV trajectories. The IRS, acting as the BD, leverages beamforming to enhance the reverse scattering effect while

¹Although the articles in Table II do not provide an extensive description of the channel estimation process, the choice of channel models partially reflects the channel estimation. The same with Tables III and IV.

					Involved issues					
Categories				Bear mi	nfor- ng	Reso alloc	ource ation	uo	tions	ions
	Ref.	Description	Channel estimation	Active beamforming	Passive beamforming	Transmission power	Computing resources	Trajectory optimizati	Low power communicat	Sustainable communicat
BackCom	[120]	An AO algorithm based on fractional program, semidefinite program, and RL to maximize total reception rate of all users.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	\checkmark	×
	[66]	An AO algorithm based on semidefinite program, SCA, and RL to maximize the broadcast secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	\checkmark	×
SWIPT	[51]	An optimization algorithm based on Lagrangian dual to maximize the average harvested energy.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[30]	An iterative algorithm based on SCA and BCD to maximize the minimum average achievable rate.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[52]	An AO algorithm based on SCA, penalty function method, and difference-convex programming to maximize achievable sum-rate for all users.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[29]	An AO algorithm based on convex programming and SCA to minimize the maximum energy consumption.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[45]	A double iteration algorithm to maximize average achievable rate over time slots.	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[53]	An AO algorithm to minimize UAV's total flying time.	\checkmark	×	\checkmark	×	\checkmark	\checkmark	\checkmark	×
	[27]	A two-phase approach to improve the global EE of the system.	\checkmark	×	\checkmark	×	×	\checkmark	\checkmark	×
Other sys- tem EE optimisation	[46]	An AO algorithm and DNN to minimize average system energy consumption.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	\checkmark	×
	[47]	A DL based algorithm to minimize energy consumption.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	\checkmark	×
	[54]	An AO algorithm based on SDR to maximize the EE.	\checkmark	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×
	[121]	An AO algorithm to maximize the EE.	\checkmark	\checkmark	\checkmark	×	×	×	\checkmark	×
	[83]	An iterative algorithm based on SCA and Dinkelbach's method to maximize the spectrum efficiency and the EE.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	\checkmark	×
	[122]	An approach based on deep Q-network and SCA to minimizie total transmit power.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	\checkmark	×

The symbol " \surd " represents the article satisfies the property, and " \times " represents not.

ensuring low energy consumption, and it transmits information to users via RF signals. In [120], authors formulate a problem to maximize the reception sum rate of all users under constraints of UAV transmission power and trajectory, as well as IRS reflection coefficients. Due to the existence of multiple deeply coupled variables, the problem is decomposed into three sub-problems using Block Coordinate Descent (BCD), and an Alternating Optimization (AO) algorithm is proposed to iteratively solve each subproblem. Compared to traditional BackCom, BackCom in an IRS-assisted UAV communications framework exhibits cost-effectiveness and EE. Unlike [120], authors in [66] study the BackCom communication system in the presence of multiple illegal eavesdroppers, considering both system energy consumption and security.

Lesson 1: While IRSs can replace traditional BDs for low-

power communications, how to reasonably arrange the location and the number of IRSs to maintain the system communication requirements still needs to be investigated. Additionally, Back-Com needs to consume the energy of the UAV to activate the reflected signal, so the energy consumption of UAVs should also be considered in the system design. Furthermore, in order to reduce the transmission energy consumption of communications, the approach of jointly modulating environmental signals and RF signals is also worthy of further research.

2) SWIPT for Energy-Constrained Communications: SWIPT is an evolution of wireless power transfer that utilizes the properties of wireless signals to couple energy into signals for simultaneous transmission. As shown in Fig. 4, users can receive both information and energy via the wireless signal, which can improve the lifespan of network nodes and provide



Fig. 4: Schematics of SWIPT in IRS-assisted UAV communications.

a boon for energy-limited IoT devices [125]. In IRS and UAV assisted SWIPT systems, IRSs can optimize the wireless channel and reduce the loss of energy transmission [126], [127], while UAVs can be used as mobile relays or airborne RF sources to enhance the transmission efficiency of the signal by adjusting their positions with the ground nodes or IRSs. It is worth noting that the power distribution ratio has a direct impact on the efficiency of user energy harvesting and information transmission.

SWIPT can be also widely used in IRS-assisted UAV communication scenarios with energy-constrained devices. Authors in [51] investigate an IRS and UAV-assisted SWIPT system to maximize the average harvested energy of users, and formulate a joint optimization problem of UAV trajectories, power allocation ratio, and IRS phase shift. A method based on Lagrangian dual algorithm is proposed to solve the formulation problem, aiming to overcome the drawback of traditional BCD-SCA methods, which are sensitive to initial parameters.

Authors in [30], [52] investigate multi-user SWIPT scenarios, different from single-user scenario mentioned in [51]. In order to satisfy communication requirements of multiple users, authors in [30] propose a Time-Division Multiple Access (TDMA) scheduling protocol when the UAV flies along an optimized trajectory. It divides the transmission time into different time slots to ensure that each IoT device is allocated with a specific slot for energy and information transmission. Unfortunately, authors in [30] use a simple linear SWIPT model, which results in energy saturation at high power levels and difficulty in energy harvesting at low power levels. Instead, authors in [52] propose a non-linear SWIPT framework with IRS-assisted UAV communications for energy-limited IoT devices. This article uses Successive Interference Cancellation (SIC) to eliminate interference among different users when adopting the NOMA scheme. Specifically, the channel gains of all users are first estimated and sorted, and then the user with stronger channel power helps the user with weaker channel power to decode the signal, and finally, its own signal is decoded.

Authors in [29] study the three-dimensional trajectory of

the UAV, which is different from studies that assume the UAV moves at a fixed altitude in [30], [51], [52]. An onboard IRS is utilized to enhance the uplink signal in a non-linear SWIPT system. Considering the impact of UAV's three-dimensional trajectory on system performance, authors optimize UAV trajectories, IRS phase shift, and user scheduling to minimize energy consumption for all users.

Authors in [45] compare the performance of perfect CSI and statistical CSI for IRS-assisted UAV communications in SWIPT systems, which is contrary to the assumption that the system can obtain perfect CSI in [29], [52]. Authors optimize the power allocation ratio, transmission beamforming, UAV trajectories, and IRS phase shift to maximize the average achievable reception rate during UAV flight slots. Simulation results show that statistical CSI performs worse than perfect CSI, but statistical CSI is more suitable for practical applications.

Lesson 2: In IRS-assisted UAV communications, energy and communication demands are constantly changing. As a result, an adaptive power allocation ratio is advantageous. In addition, the distance of UAVs from IRSs and users affects the effectiveness of information and energy received by users, and the flight of UAV consumes a large amount of energy. Therefore, it is worth considering how to balance the energy consumption of UAV flight and the effect of wireless power transfer.

3) Other Methods for Energy-Constrained Communications: In addition to SWIPT and BackCom, optimizing specific performance metrics such as EE is another way to address energy-constrained communication issues. Besides, it's worth noting that authors in [128] illustrate that solar energy can alleviate the energy issues of UAVs and their supporting communication devices. Due to the complexity of hardware design, uneconomical energy consumption caused by the weight of solar panels, and a heavy reliance on weather conditions, the use of solar energy is limited. Since the placement of IRSs affects UAV flight trajectories, which is also closely related to UAV propulsion energy consumption, the improvement of EE from the perspective of IRS placement is introduced in the following content.

Ground IRS placement on buildings is considered in [27], [46], [53]. Authors in [53] construct a problem of jointly optimising UAV trajectories, IRS phase shifts, scheduling of ground nodes and computational resource allocation to minimize the total flight time of the UAV, thus overcoming the energy-constrained issue of IRSs and UAV-based MEC systems. Unlike the linear discharge of the UAV battery in [53], the nonlinear discharge is discussed in [27]. Authors first propose an algorithm to estimate the flight time of the airborne UAV, and then optimize the IRS phase shift matrix and deployment position. Finally, the UAV flight trajectory is optimized based on the estimated UAV flight time and optimized IRS deployment position to improve the global system EE. In particular, this system considers practical constraints such as discrete phase compensation of the IRS and phaseamplitude relationships.

Authors in [46] approximate effective channel gain by Deep Neural Network (DNN) models based on imperfect CSI,

which is different from [27], and conduct research on the average system energy consumption minimization problem to jointly optimizie UAV trajectories, IRS phase shifts, and resource allocation strategies by an AO approach. Similar to [46], imperfect CSI and other system design constraints, such as UAV flight jitter, and practical hardware constraints are also taken into account in [47]. In order to minimize energy consumption of the UAV, authors jointly optimize UAV trajectories, UAV active beamforming, and IRS passive beamforming. Specifically, to alleviate the challenges of obtaining the real-time varying CSI of IRS-UAV, UAV-user, and IRSuser links under UAV jitter and system hardware constraints, the authors propose a hybrid semi-unfolding DNN.

In fact, placing IRSs on UAVs can achieve flexible deployment of IRSs while ensuring their support for communications [54], [121]. The flexibility of airborne IRS is reflected in the fact that it is easier to establish LoS links compared to groundbased IRS, while allowing flexible reflections from all angles. In order to maximize the EE of aerial IRS-assisted UAV communication systems, authors in [54] optimize the user transmit power, BS active beamforming, and IRS passive beamforming under user minimum transmit rate and power constraints. It is worth noting that deploying aerial IRSs near users rather than BSs leads to a more pronounced enhancement in system EE. Polarisation technologies allow signals of the same frequency to be transmitted in different polarisation directions and are considered to be an effective method of achieving multimode transmission. In [121], authors introduce polarization technologies in an aerial IRS communication system, propose an energy-efficient framework for joint broadcast-unicast communication and jointly optimize passive beamforming of IRSs and active beamforming of BSs. However, to simplify the system model, authors in [54], [121] assume all CSI can be perfectly obtained.

Authors in [83] study trajectory optimization of UAVs equipped with IRSs, unlike the static deployment of UAVs equipped with IRSs [54], [121]. The goal of trajectory optimization is to minimize the propulsion energy consumption of UAVs while ensuring the system's service quality. Authors jointly optimize UAV trajectories, active and passive beamforming to achieve a balance between achievable reception rates and energy consumption, thereby improving the energy and spectral efficiency of the system. Furthermore, for trajectory optimization, authors use SCA and first-order Taylor expansion to reformulate the problem and adopt the Dinkelbach method to solve it. Similar to [83], authors in [122] aim to minimize the transmit power of a communication system aided by multiple UAVs carrying IRSs under heterogeneous networks. Each aerial IRS has the capability to adjust its position and phase shift to serve users with poor channel conditions. To tackle the formulated highly non-convex problem, authors decompose it into two subproblems, and employ the dueling deep Q network and SCA to sequentially solve them.

Lesson 3: The flight energy consumption of UAVs is usually the main component of the total energy consumption in UAV communication systems, which requires special attention. Specifically, the computational energy consumption of algorithms can directly impact the UAV's battery life and





Fig. 5: Schematics of malicious jamming in IRS-assisted UAV communications: (a) aerial IRS scenes; and (b) ground IRS scenes.

performance. To be precise, on one hand, excessive computational energy consumption can reduce the UAV's flight time. On the other hand, it might cause the system to overheat, thereby affecting the UAV's stability and safety. Therefore, it's essential to develop lightweight, low-complexity trajectory optimization algorithms.

B. Solutions for Secure Communications

In IRS-assisted UAV communications, malicious jamming and eavesdropping attacks are the most common attacks, and can be also effectively defended against through system design and optimization without over-reliance on network protocols, encryption techniques, and identity authentication. Thus, we take these two security threats as examples and provide a detailed overview of existing solutions for secure communications. Common anti-jamming and eavesdropping methods are summarized in Table III, including Physical Layer Security (PLS) technologies and covert communications.

1) PLS Technologies to Resist Malicious Jamming: PLS technologies utilize the characteristics and corresponding technologies of the physical layer to protect communication channels and transmission media, enabling secure communications. In general, the PLS method focuses on the wireless environment and the physical characteristics of both IRSs and UAVs. As shown in Fig. 5, leveraging the maneuverability of UAVs, the trajectory of UAVs is set in advance, allowing them to move away from jamming sources and reduce the impact of jamming on communication performance [130], [131].

The use of passive beamforming by IRSs can effectively suppress jamming signals while controlling excessive energy consumption of the system. Authors assume two scenarios in [55]: one with the IRS deployed in an area far from the jamming source, and the other with that near the jamming source. They optimize UAV trajectories, passive beamforming of IRSs, and transmission power of ground networks to maximize the UAV's average reception rates in the wireless environment where jamming is present. The numerical results show that deploying the IRS near the jamming source rather than far from it can provide better performance for the system.

			Technologies							lved ues
Categories			5	Bear mi	nfor- ng	Resource allocation		ion	50	ks
	Ref.	Description	Channel estimation	Active beamforming	Passive beamforming	Transmission power	IRS	Trajectory optimizat	Malicious jammin	Eavesdropping attac
	[55]	An AO algorithm based on SCA and SDR to maximize the average transmission rate.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	\checkmark	×
	[35]	An iterative algorithm based on AO algorithm, SDR and SCA to maximize the EE.	\checkmark	×	\checkmark	×	×	\checkmark	\checkmark	×
DI G	[56]	A DRL-based defensive deception approach to realize efficient communications.	\checkmark	×	\checkmark	\checkmark	×	×	\checkmark	×
	[48]	An optimization algorithm based on distributed matching and Q-learning to maximize achievable communication rates.	\checkmark	×	\checkmark	×	\checkmark	×	\checkmark	×
	[65]	An iterative algorithm based on SCA to maximize the average secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×	\checkmark
technologies	[49]	An AO algorithm based on SCA and SDR to maximize the worst-case sum secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×	\checkmark
	[34]	An AO algorithm based on BCD, SDR and SCA to maximize the average secrecy rate.	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark	×	\checkmark
	[41]	An AO algorithm based on SDR to maximize the system secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×	\checkmark
	[66]	An AO algorithm based on RL, SCA, and semidefinite program to maximize the broadcast secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×	\checkmark
	[50]	An optimization algorithm based on DL to maximize the total system secrecy rate.	\checkmark	\checkmark	\checkmark	×	×	\checkmark	×	\checkmark
Covert communica- tions	[67]	An AO algorithm based on SCA to maximize the average transmission rate.	\checkmark	×	\checkmark	×	×	\checkmark	\checkmark	\checkmark
	[57]	An Optimization methods based on closed-form solutions to maximize the covert transmission rate.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	\checkmark	\checkmark
	[38]	A block SCA algorithm to minimize average EE.	\checkmark	×	\checkmark	\checkmark	×	\checkmark	\checkmark	
	[129]	Mathematical analysis and derivation to maximize the worst-case transmission rate.	\checkmark	×	×	×	×	×	\checkmark	\checkmark

The symbol " $\sqrt{}$ " represents the article satisfies the property, and " \times " represents not.

The accuracy of the CSI about the jamming channel directly affects the anti-jamming effect. Authors in [35] analyze the EE of the system under imperfect CSI jamming, unlike the ideal channel in [55]. They formulate a nonconvex problem of jointly optimizing UAV trajectories and IRS beamforming, and solve it using an iterative algorithm based on AO, SDR, and SCA. Although the system performance is reduced compared to the perfect CSI, analyzing jamming attacks under imperfect jamming CSI is more realistic.

Defensive deception strategies are also used to resist jamming attacks, by misleading and confusing attackers into believing the success of their attacks. Authors in [56] propose a combination of defensive deception and ML to resist jamming attacks, in which a Deep Reinforcement Learning (DRL)-based power allocation scheme combined with passive beamforming by IRSs aims to obfuscate the attack surface and lure the jamming attack to the designated channel, with the purpose of achieving anti-jamming effects.

The anti-jamming scenarios described above in [35], [55], [56] are static scenes for IRSs. As Fig. 5a shows, in order to provide IRSs with the same maneuverability as UAVs, authors in [48] propose to place the IRSs on the UAVs and investigate the anti-jamming scenario where the jamming source location is uncertain. To maximize the system's antijamming performance, author jointly optimize the selection of IRS and beamforming. In particular, authors propose a game-theory-based distributed matching selection algorithm to address the matching problem between IRS-equipped UAVs and multiple users. Furthermore, a Q-learning-based beamforming algorithm is proposed to mitigate the impact of CSI



Fig. 6: Schematics of eavesdropping attracks in IRS-assisted UAV communications: (a) ground eavesdropper scene; and (b) aerial eavesdropper scene.

acquisition accuracy on the system's anti-jamming capability. Unlike the study in [48], authors in [132] study the system performance of IRS-assisted UAV communications in freespace optical systems under malicious UAV jamming. Compared with ground jamming, UAV-mounted jamming sources change positions when the UAV moves, making it difficult to detect and track the jamming source. The authors also derive closed-form expressions for the end-to-end average Bit Error Rate (BER) and average outage probability, emphasizing advantages of IRSs under aerial jamming resistance.

Lesson 4: The accuracy of predicting the location of jamming sources determines the effectiveness of IRS beamforming technology to resist jamming. Therefore, it is necessary to research how to predict the location of jamming sources using only available CSI information, especially in dynamic jamming environments. Furthermore, in order to improve the accuracy of jamming source location prediction, the introduction of a feedback mechanism can be considered, which means that the communication device can periodically report information about the jamming source to help the system adapt to the dynamic environment.

2) **PLS Technologies to Resist Eavesdropping Attacks**: Relying on its unique advantages at the physical layer, PLS technologies can also play a role in countering eavesdropping in UAV communication scenarios. However, its performance may still be affected by the specific scene [5], [34], [49], [65], [66] and device constraints [36], [50]. Additionally, the combination of PLS technologies and artificial noise can further enhance the anti-eavesdropping performance of UAV communications [41].

Relevant PLS technologies of countering ground eavesdroppers are studied in [49], [65]. Authors in [65] focus on the single-user and single-eavesdropper scenario, where the IRS is fixed on the ground to achieve the maximum secrecy rate of the system through passive beamforming of the IRS, active beamforming of the transmitted signal, and UAV trajectory optimization. Unlike the assumption in [65] where the system can accurately obtain the eavesdropper's location information and CSI, authors in [49] consider that the eavesdropper's location is unknown. Although the exact 16

locations of eavesdroppers are not known, their approximate positions can be locked into a circular area by the UAV's aerial target detection. Hence, authors derive the worst-case secrecy rate of legitimate users and use this to formulate a problem for jointly optimising the phase shift of the IRS, the transmitted beamforming and the hovering position of the UAV. The formulated problem is solved by an AO algorithm based on SCA and SDR to maximize the worst-case secrecy rate of all system users.

PLS technologies can also be used to solve the security problem caused by airborne eavesdroppers. As shown in Fig. 6b, aerial eavesdroppers based on UAVs can easily establish a LoS link with the ground BS, and these channels facilitate the reception of eavesdroppers' signals. Therefore, compared with ground eavesdroppers, airborne eavesdroppers pose more serious security threats to the network. Authors in [34] study the security of a single airborne user in the presence of multiple airborne eavesdropper scenarios. Faced with a scenario where both the user and eavesdroppers are in the air, three-dimensional trajectory optimization of the UAV is more advantageous than two-dimensional trajectory optimization when adjusting distances among users, IRSs, eavesdroppers, and BSs. Unlike the use of a virtual antenna array constructed by a drone swarm [133], authors use the IRS to achieve energy-efficient secure communications. By jointly optimizing the transmission power, active and passive beamforming, and the UAV's three-dimensional trajectories, the system's secrecy rate is improved.

The combination of PLS technologies and artificial noise can achieve enhanced anti-eavesdropping performance of UAV communications. Artificial noise can introduce interference, preventing eavesdroppers from accurately capturing the original signal. The use of artificial noise and PLS technologies against eavesdropping attacks is investigated in [41]. The authors consider a scenario in which a ground eavesdropper eavesdrops on airborne BS signals. By simultaneously introducing artificial noise and employing both active and passive beamforming, the eavesdropper's signal interception quality is disturbed. Furthermore, the authors optimize the deployment locations of UAVs and IRSs to maximize the system's secrecy rate.

For the anti-eavesdropping communication scenario involving multiple UAVs, as shown in Fig. 6a, some IRSs and UAVs can act as friendly jammers to interfere with eavesdropping, and other IRSs and UAVs can compensate for the reduced received quality caused by artificial noise [5]. Authors in [66] also consider the broadcast secrecy rate of BackCom in scenarios with multiple eavesdroppers. The signals emitted by the UAV, serving as the carrier for IRS information transmission, can cause certain interference to both users and eavesdroppers. Therefore, they optimize the UAV's trajectory to balance the actual impact of UAV transmission signals on user interference, eavesdropper interference, and IRS information transmission. At the same time, passive beamforming for the IRS and active beamforming for the UAV are jointly optimized.

Regrettably, in the aforementioned process of using PLS technologies to address eavesdropping attacks [34], [49], [65],

[66], perfect CSI is assumed, which is not consistent with actual scenarios, especially in situations where positions of the eavesdropper and jamming sources are unknown. This issue is discussed in [36], where authors assume perfect channel estimation between the BS and the IRS, as well as between the IRS and users, but only partially available CSI for the channel between the IRS and the eavesdropper. By deriving expressions of probability density function and moment generating function of the instantaneous secrecy rate, the system's secrecy rate is analyzed. Similar to [36], authors in [50] investigate the secure transmission problem of IRS-assisted UAV mmWave communication in the presence of imperfect CSI. They jointly optimize active/passive beamforming and UAV trajectories to maximize the system secrecy rate. In particular, to overcome the challenges posed by high coupling of CSI and UAV trajectories, authors propose a DRL algorithm based on the two-deep deterministic policy gradient framework, which has a strong decoupling capability. Specifically, the first policy gradient is used for active and passive beamforming while the second policy gradient is used for trajectory optimisation of the UAV.

Lesson 5: The effectiveness of PLS technologies to counter eavesdropping attacks heavily relies on accurate CSI of the eavesdropper. Currently, acquiring CSI remains challenging, making it necessary to investigate methods for obtaining relatively accurate CSI of eavesdroppers. Additionally, traditional communication protocols and encryption technologies can offer good eavesdropping resistance, but adapting them to specific scenarios of UAV communications requires further consideration. Furthermore, measures taken by the system to counter eavesdropping attacks often introduce additional overhead, prompting researchers to strike a balance between system security and other performance metrics.

3) Covert Communications to Resist Malicious Jamming and Eavesdropping Attacks: Another way to address the security threats of UAV communications is covert communications. It is also known as low probability of detection communications, and utilizes randomization techniques such as artificial noise and power control to conceal transmitted signals within environmental noise or artificial uncertainties, aiming to reduce the detectability of the transmission. More importantly, when covert communications are utilized for wireless information transmission, the signal should not be perceivable by eavesdroppers [134].

As a complement of PLS technologies to resist eavesdropping attacks and malicious jamming, covert communications are also extensively studied in [57], [67]. Authors in [57], [67] investigate the covert transmission rate of the aerial IRSassisted covert communication system. They first determine the optimal detection threshold and derive the error detection probability for eavesdroppers. Then, they formulate an optimization problem with variables of UAV trajectories and IRS phase shifts to maximize the covert transmission rate, and solve it by deriving a closed-form solution and an AO algorithm. Different from [67], authors in [57] consider the uncertainty of the eavesdropper's location and optimize the signal transmission power.

The combination of artificial noise and covert communica-



Fig. 7: Schematics of covert communications in IRS-assisted UAV communications.

tions can further enhance the security of UAV communications. As shown in Fig. 7, artificial noise can interfere with illegal users to confuse them to determine whether a legitimate user is communicating. This approach is investigated in [38], [129]. Different from the above mentioned articles [57], [67], where all UAVs serve as one role, authors in [38] consider that UAVs undertake two distinct roles: one is used to carry the IRS for reliable data transmission, and the other acts as a collaborative jammer to enhance the secrecy of the transmission. A power-efficient multi-UAV covert communication scheme is designed for scenarios with multiple eavesdroppers in the THz frequency band. In particular, an optimization problem is constructed to both improve the throughput of covert communications and reduce energy consumption of UAVs, which is iteratively solved by the block SCA method. Unlike the scenario of two different role UAVs in [38], authors in [129] set up the legitimate receiver using full-duplex mode to receive signals while also generating jamming signals to further ensure the confidentiality of covert communications. Through theoretical analysis and derivation of the proposed system, the effectiveness of the scheme is proven.

Lesson 6: Covert communications enhance the security and privacy of data, making it difficult for unauthorized users to detect or interfere with the communication content. But extended communication durations increase the risk of communication exposure. Therefore, to enhance the performance of covert communications, multi-modal communication approaches that include both communication and silence modes are worth researching. Furthermore, in practical scenarios where eavesdropping and interference are encountered, covert communications can be used as a supplement and combined with other methods to achieve security outcomes.

C. Solutions for Enhanced Communications

Up to now, researchers have proposed many solutions for enhanced communications, which typically focus on performance metrics including network rates, network latency, coverage ranges, spectrum efficiency, and reliability. In the following, we introduce relevant solutions for enhanced communications based on these system metrics, and summarize them in Table IV.

1) Enhanced Communications for Network Rate Improvement: The network rate is the most crucial metric in wireless transmission and is also the joint result of various factors. Specifically, interference management [40], [42], [58], communication links [59], [135], hardware constraints [60], and multi-user spectrum resource allocation [43], [44] all have impacts on the network rate.

The effectiveness of interference management directly impacts the signal transmission quality, thereby affecting the network throughput of the UAV communication system assisted by IRSs. Beamforming design is an effective approach to mitigate interference. Generally, beamforming generates specific directional beams while reducing signal interference in other directions, thus enhancing the link quality. Authors in [58] investigate the impact of IRS beamforming on the sum network rate in IRS empowered UAV downlink communication networks. By virtue of beamforming of IRSs, signal interference of multiple users is reduced. Similarly, authors in [40] formulate the problem of maximizing the minimum average achievable rate in a UAV scenario supporting THz communications. In this case, beamforming not only affects interference among multiple users but also plays a crucial role in reducing path loss at high frequencies. The authors jointly optimize the phase shift of the IRS, UAV trajectories, THz bandwidth allocation and power control. However, it is worth noting that in [40], [58], only the IRS phase shift is optimized, and the reflection coefficient is fixed.

In fact, the adjustment of IRS amplitudes can also further enhance the interference management effect of beamforming. Authors in [42] study orthogonal frequency division multiple access-based UAV communications. In order to maximize the system sum-rate while satisfying heterogeneous service quality requirements of each user, authors optimize phase shifts and amplitudes of IRSs. Furthermore, to address the formulated non-convex optimization problem, the authors employ the AO algorithm to obtain suboptimal solutions with lower-bound results.

In an aerial IRS scenario, UAV trajectories affect the quality of LoS links [59], [135]. Authors in [135] discuss the scenario of an airborne IRS assisting multiple GUs. In order to maximize the minimum average transmission rate, the authors optimize the trajectory of the UAV, the phase shift of the IRS, and the communication scheduling. Different from the aforementioned IRS-assisted UAV communication scenarios, where UAVs only play a role as BSs [40], [42], [58] or active/passive relays [135]. The UAVs play two important roles in [59], with the main UAV acting as an airborne RF transmitter and the auxiliary UAV acting as a passive relay to enhance the signal reception of GUs. To maximize the cumulative system throughput, authors jointly optimize trajectories of multiple UAVs and the transmission power of the main UAV, and propose an algorithm based multi-agent DRL to solve the optimization problem.

Authors in [60] focus on imperfect IRSs, which is different from the ideal IRS-assisted UAV communications in [40], [42], [58], [59]. In fact, the enhancement of system gain by IRSs largely depends on the reliability of phase estimation and cophase processes. To alleviate the impact of IRS imperfections, the phase estimation error of IRSs can be taken into account in the practical system design and optimization [138]. In [60], authors study the joint IRS element and power allocation problem in the presence of phase estimation and compensation errors. The objective is to maximize the total reception rate of the UAV while satisfying energy constraints and minimum reception rate requirements of individual UAVs. To meet the finite phase configuration frequency of the IRS panel, TDMA technology is used, and each IRS element is only used once in each TDMA frame. A heuristic algorithm based on the estimated phase quality of IRS elements is proposed to solve the problem.

NOMA technology is a commonly used method to enhance the network rate in multi-user scenarios. It provides services for multiple users by dividing a subcarrier into different power levels, allowing users to share the same frequency and time resources while using different signal powers and codewords to differentiate among users. To eliminate interference among different users, interference-cancellation technology such as SCA is often employed. Besides, the system performance brought by NOMA depends on the differences in wireless channels among different users, with greater channel differences resulting in better system performance. Traditionally, wireless channel gain has been thought to be entirely determined by the environment, which means that the differences in randomness can severely affect the performance of NOMA. Fortunately, the reconfiguration of wireless environments by IRSs can change the design paradigm of NOMA.

In order to improve the network rate, in NOMA-based IRS-assisted UAV communication scenarios, the decoding order of NOMA users is typically jointly optimized along with other variables, including the association between IRSs and users, as well as the transmit power allocation [43], [44]. However, solving the proposed optimization problem is challenging due to its non-convexity and the coupling between the user decoding order and the relationship coefficients with IRSs. To address this issue, authors of [43] propose a sequence interference extension method that converts the IRS association problem into a convex optimization problem by decoupling user association and SIC decoding. Different from [43], authors in [44] propose an iterative algorithm based on BCD, which first decomposes the problem into subproblems including UAV placement and decoding order determination, IRS phase shift matrix design, and UAV transmission power optimisation. Then, it uses penalty-based methods and SCA techniques to solve the first two problems. Finally, by fixing other variables, SCA is used to solve the third subproblem.

Lesson 7: In the above optimization process, the channel model of the system is basically simplified. In practice, simplistic and idealized channels basically do not exist. Therefore, researchers should focus on robust system design in the presence of channel estimation errors, especially for the system design in mmWave and THz bands. In addition, in scenarios with a large number of users, the collaboration of multiple IRSs and UAVs becomes particularly crucial for improving network rates. It's worth noting that the UAV is relatively cost-effective compared to the IRS, so cost factors for the both should be considered in practical system design.

2) Enhanced Communications for Latency Reduction: In IRS-assisted UAV communications, most research has focused on the communication propagation process to reduce latency.

		. Description	Technologies									Involved issues					
				Beamf- orming		Resource allocation					nt		ints	s	ß		
Metrics for perform- ance optimiza- tion	Ref.		Channel estimation	Active beamforming	Passive beamforming	Transmission power	IRS	Computing resources	Frequency	Trajectory optimization	Difficulties of interference managem	Shortage of spectrum resources	Challenges of IRS and UAV deployme	Complexity of wireless environment	Nonconvexity of multivariate couplir		
	[58]	An AO algorithm based on BCD to maximize the total reception rate of users.	\checkmark	×	\checkmark	\checkmark	×	×	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark		
	[40]	An iteration algorithm based on SCA to maximize the minimum average achievable rate of users.	\checkmark	×	\checkmark	\checkmark	×	×	\checkmark	\checkmark	\checkmark	×	\checkmark	×	\checkmark		
[42] Network rates [59] [60] [43] [44] [136]	[42]	A parametric approximation method and AO algorithm to maximize the total reception rate of users.	\checkmark	×	\checkmark	\checkmark	\checkmark	×	\checkmark	\checkmark	\checkmark	×	\checkmark	×	\checkmark		
	[135]	An AO algorithm based on SCA to maximize the minimum average transmission rate.	\checkmark	×	\checkmark	×	×	×	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark		
	[59]	A multi-agent DRL based algorithm to maximize the total throughput.	\checkmark	×	×	\checkmark	×	×	×	\checkmark	×	×	\checkmark	×	\checkmark		
	[60]	A centralized algorithm to maximize the total reception rate of UAVs.	\checkmark	×	\checkmark	\checkmark	\checkmark	×	×	×	\checkmark	×	×	\checkmark	\checkmark		
	[43]	A three-stage optimization algorithm to maximize the total reception rate of users.	\checkmark	×	\checkmark	×	\checkmark	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark		
	[44]	An iterative algorithm based on BCD to maximize the total reception rate of users.	\checkmark	×	\checkmark	\checkmark	×	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark		
	[136]	A RL-based approach to maximize the downlink transmission capacity.	\checkmark	×	\checkmark	×	×	×	×	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark		
	[137]	An optimization algorithm based distributional RL to maximize the total reception rate of users.	\checkmark	\checkmark	\checkmark	×	×	×	×	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark		
	[61]	An AO algorithm based on SCA and double deep Q-network to reduce statistical delay and error rates of users.	\checkmark	×	×	×	\checkmark	×	×	\checkmark	×	×	\checkmark	×	\checkmark		
Latency [[62]	An AO algorithm based on SCA and Dinkelbach's transform to reduce statistical delay and error rates of users.	\checkmark	\checkmark	\checkmark	\checkmark	×	×	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark		
	[39]	An iterative algorithm based on Hungarian algorithm and whale optimization algorithm to reduce total network latency.	\checkmark	×	\checkmark	×	×	\checkmark	\checkmark	×	\checkmark	×	×	×	\checkmark		
	[103]	An optimization algorithm based on differential evolution, clustering algorithm, and greedy algorithm to minimize the total system cost.	\checkmark	×	\checkmark	×	×	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark		
[63]	[63]	An iterative optimization algorithm to maximize the throughput of SUs.	\checkmark	×	\checkmark	\checkmark	×	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark		
efficiency	[64]	An algorithm based on relaxation and penalty to minimize weighted sum BER among all IRSs.		×		×	\checkmark	×	×	\checkmark	\checkmark	\checkmark	\checkmark	×	\checkmark		
Others	[107]	An AO algorithm based on binary integer linear programming and soft actor-critic algorithms to maximize the minimum achievable rate of users.	\checkmark	×	\checkmark	×	×	×	×	\checkmark	\checkmark	×	\checkmark	×	\checkmark		

The solutions primarily involve high-frequency communications [136], [137] and Finite Blocklength Coding (FBC) [61], [62], [139]. There are also a few studies [39], [103] aiming to enhance the computational capabilities of the system.

Using frequency bands such as mmWave and THz for communications is an effective method to improve transmission latency and alleviate spectrum scarcity to some extent. Authors in [136], [137] consider mmWave-based airborne IRS-assisted communications. In order to maintain the LoS channel for mmWave communications, authors in [136] use an RL-based approach to simulate the radio channel, and optimize the phase shift and deployment location of the IRS. Building upon [136], authors in [137] introduce the optimal precoding matrix for the BS to further enhance the system's performance. To address the difficulty of LoS channel maintenance brought by the uncertainty of mmWave channels, a distributional RL algorithm is proposed to dynamically optimize locations of the airborne IRS.

The use of FBC can also reduce the latency in IRS-assisted UAV communication systems. FBC refers to appropriate encoding within a given length of data blocks, allowing the receiver to determine whether the sent data is correct within a limited time. Its feasibility in IRS-assisted UAV communication systems is demonstrated in [139], and the system design of FBC-based IRS-assisted UAV communications is discussed in detail in [61], [62]. In [61], authors investigate massive ultra-reliable and low-latency communications in 6G networks supported by IRS-assisted UAV communications. To reduce transmission latency and meet the error-rate bounded quality of service, authors jointly optimize the UAV's trajectory and FBC-based IRS layout. Additionally, authors solve the proposed joint optimization problem using double deep Q-network algorithms. Different from [61], authors in [62] apply the FBC technology to MEC system to meet the system requirements on latency and error rates. Considering energy consumption of edge users and UAVs, authors jointly optimize UAV trajectories, active and passive beamforming, and analyze the effectiveness of this methodology in the context of singleuser and multi-user cases.

In MEC scenarios, computational latency cannot be ignored, and its related research is discussed in [39], [103]. Multiaccess edge computing in a THz network is considered, and authors in [39] study the downlink, uplink, and computation latency on the UAV. Joint optimization of IRS phase shifts, UAV computing resources, and THz sub-bandwidth allocation is performed to reduce the overall system latency. Hungarian algorithm is leveraged to schedule sub-bandwidths, while whale optimization algorithm is used to optimize IRS phase shifts. Different from the single UAV and IRS scenario discussed in [39], authors in [103] discuss the overall cost of a collaborative MEC system with multiple UAVs and multiple IRSs, including energy consumption, latency, and maintenance costs. To minimize the total cost of the system, authors formulate a joint optimization problem based on UAV trajectories and IRS phase shifts, which is solved by a fourstage optimization algorithm based on differential evolution, clustering algorithm, and greedy algorithm.

Lesson 8: The aforementioned studies primarily focus on

communication transmission and data processing. Although they are effective in reducing latency, there is still room for improvement. On one hand, integrating the efficiency of high-frequency communication with FBC can further reduce system latency. On the other hand, rationally planning the UAV's trajectories and resource allocation based on user task requirements and servers' computational capabilities is feasible approaches. Moreover, not all tasks necessitate a low network latency. Developing an adaptive multi-modal UAV communication method tailored to delay-sensitive tasks and communication resources is important.

3) Enhanced Communications for Spectrum Efficiency Improvement: Due to the scarcity of spectrum resources, researchers' attention to spectrum efficiency is gradually increasing. Generally, CR [63], [140] and Symbiotic Radio (SR) [64], [141] are used to improve spectrum efficiency. Instead of utilizing spectrum with high frequencies, CR and SR reuse the idle spectrum to improve spectrum utilisation. Moreover, unlike multiple access technologies such as NOMA, CR and SR have an intelligent spectrum allocation strategy that avoids interference in signal transmission among multiple users.

CR is composed of PUs and SUs. When SUs share the spectrum for communications, they need to ensure the service quality of PUs. Specifically, CR technology utilizes the idle portion of radio spectra, allowing SUs to occupy these idle frequency bands for communications while generating acceptable interference to PUs, thereby improving spectrum utilization ratios.

The use of CR for spectrum efficiency improvement in IRS-assisted UAV communication systems is widely studied. Authors in [140] focus on a CR-based IRS-assisted UAV communication scenario, where SUs, including vehicles and UAVs, rely on CR to access the authorized spectrum for communications. Additionally, NOMA and IRSs are employed to maintain good system performance for SUs. To analyze the performance of CR-based IRS-assisted UAV communication systems, the authors derive the expression for the outage probability of all SUs. Authors in [63] propose a CR model based on IRS-assisted UAVs. To address the throughput degradation of SUs caused by interference from PUs, authors make the use of IRS beamforming to mitigate signal interference, and jointly optimize the UAV's trajectory and transmit power to maximize the throughput of SUs.

Building upon CR, SR can ensure good spectrum efficiency while achieving low-power communications. In fact, SR can be regarded as an improved product combining CR and BackCom, where the secondary information is generated by controlling the on/off states of reflecting elements of IRSs, and transmitted through RF signals of the primary information. The outage probability and ergodic spectral efficiency of UAV communication systems assisted by SR-based IRSs are analyzed in [141], in which the UAV equiped with an IRS act as a relay to transmit the signal from the source node to the GU. The ground secondary node modulates and uses ambient BackCom technology to relay the RF signal from the UAV-IRS environment and send information to the ground secondary receiver.

Authors in [64] optimize the performance of IRS-assisted

UAV communications based on SR in urban environments. Multiple IRSs are deployed to sense and transmit environmental information, and decoding is achieved through channel response differences. Each reflecting element of IRSs is tuned to align the signal phase of the UAV-IRS-BS link with that of the UAV-BS link, achieving coherent signal combination at the BS side. Furthermore, favorable channel conditions for UAV-BS and UAV-IRS links can be created based on the mobility of the UAV. By jointly optimizing IRS phase shift, IRS scheduling and UAV trajectories, the BER of IRSs is maximized while meeting the minimum transmission rate requirement of UAVs.

Lesson 9: In SR systems, the backscattering efficiency directly affects the system performance, so deployment locations and reflection design of IRSs are particularly important for the improvement of system spectral efficiency. In addition, in theory, NOMA technology does not degrade system performance significantly when the number of users increases. However, in practice, there are still difficulties in the decoding process to distinguish different users.

4) **Enhanced Communications for Others**: Enhanced communications of IRS-assisted UAVs are also reflected in the network coverage and communication reliability.

In order to enhance network coverage, two aspects can be considered: i) The flight altitude of the UAV can be planed to achieve a balance among transmission performance, coverage ranges, and path losses. For example, authors in [46] allow the UAV altitude to be increased when the horizontal distance between the UAV and GUs is far to strike a balance between data transfer rates and outage probabilities. ii) From the perspective of IRSs, the deployment location, reflection design, and the number of IRSs can be jointly optimized to assist the UAV in improving the coverage range. For example, to meet the wireless network requirements of trains and passengers, authors in [107] focus on IRS and UAV-assisted railway communications. High wireless network coverage can reduce frequent network switching caused by movements of high speed trains. Therefore, IRS-equipped UAVs are designed as airborne relays while jointly optimising IRS phase shifts and UAV trajectories to extend the BS signals. Similarly to [107], authors in [111] study how to effectively improve the coverage range of IRS-assisted UAV communication systems based on NOMA, mainly exploring the influence of UAV deployment density and user distribution. By analysing historical associations between UAVs and users with LoS and NLoS channels, the maximum achievable coverage probability of two users is derived and analyzed.

Improving reliability of UAV communication systems can be considered from two aspects: i) Multi-path compensation. An IRS-based multi-path compensation scheme is investigated in [142]. Specifically, at multi-antenna BSs, the signal is divided into multiple orthogonal active beams for data transmission. Subsequently, a set of IRSs reflects the orthogonal beams through different paths, and the received signals are coherently combined at the user's receiver. This approach effectively compensates for the significant multiplicative path loss induced by multipath communications. ii) Multi-user interference management. Common multi-user interference management methods include beamforming, multiple access technologies, and resource allocation. Authors in [54], [143] focus on the signal in a specific direction to reduce the received interference from non-target users by beamforming through IRSs. Authors in [43], [44] study multiuser communications based on NOMA and use SIC technique to decode user received signals and eliminate interference among different users. In addition, adjusting the transmission power of each user based on the channel quality and user location information can also reduce the signal interference among multiple users [60].

Lesson 10: In summary, enhancing network coverage and communication reliability requires consideration from multiple aspects, mainly includes reflections of IRS and positional design of IRSs and UAVs. Moreover, they are contradictory metrics, and their balance needs special consideration in different scenarios. Although increasing the flight altitude of UAVs and the deployment altitude of IRSs can enhance the network coverage, the practical system design usually has an altitude limitation, which is not considered in the above articles. In addition, the above articles ignore the fact that UAV flight can inevitably generate jitter, which should be solved by efficient beam tracking techniques.

IV. RESEARCH CHALLENGES AND OPEN ISSUES

Although IRS-assisted UAV communications can address various issues, it still faces many challenges and research opportunities in the face of the continuous development of future 6G networks. The specific discussions are as follows.

A. IRS Reflective Unit Scheduling in IRS-Assisted UAV Communications

With the reconstruction capability of IRSs, it is possible to improve the communication quality for UAVs. However, this advancement is based on relatively ideal conditions. In practical system designs under non-ideal circumstances, challenges still exist regarding the selection and scheduling of IRS reflecting units.

1) Selection of IRS Reflecting Units in Non-Ideal Conditions: Most research on IRSs focuses on system performance improvement brought by a single IRS or multiple IRSs, ignoring the fact that the IRS is composed of a finite number of reflecting units. In early research on IRSs, most assumptions are made based on the ideal IRS. In fact, both IRSs and transceivers have different degrees of hardware limitations and defects [12], and it is often not feasible to correct the phase shift of the IRS using ideal phase compensation techniques [144]. Specially, the phase errors of each reflecting unit are not the same [145]. In this case, increasing the number of IRSs may lead to a decrease in system performance, and the reason for this phenomenon is the introduction of reflecting units with larger phase errors due to non-ideal phase estimation and compensation methods [146]. Therefore, how to choose the reflecting units of IRS to improve the performance of UAV systems is worth investigation in future research.

2) **Optimal Allocation of IRS Reflection Units:** The selection of specific reflecting units of IRSs may result in idle reflecting units. How to make reasonable use of these idle reflecting units is deserved to investigate. In fact, unused reflecting units of IRSs can be reconfigured to serve other users. On the one hand, due to the randomness of wireless network environments, certain reflecting units may perform poorly for specific users and scenarios, but not necessarily in other scenarios, providing an opportunity for differentiated services of IRS reflecting units. On the other hand, the rational use of idle reflecting units can reduce the number of IRSs, mitigating the cost of network deployment to a certain extent.

B. Hybrid Active and Passive IRS-Assisted UAV Communications

The potential of passive IRSs to enhance system gains has been extensively studied, but there are still some overlooked issues that result in limited performance improvements.

1) Active IRS-assisted UAV Communications: Up to now, most of the designed IRS are passive in IRS-assisted UAV communications. However, in some special scenarios, the performance of passive IRSs cannot be guaranteed. For example, in IoT data collection system, IoT devices have low transmission power, making signals prone to loss. In addition, the "double fading" effect is an unavoidable problem, which may result in limited performance gains compared to the direct link signal without IRSs [147]. The active IRS, which equips each reflection unit with a power amplifier, is considered as an effective method to solve this problem. In addition to possessing characteristics of passive IRSs, active IRSs can amplify the reflected signals, enabling network transmission devices to achieve effective communication with lower-power signals.

However, active IRSs bring two challenges to the design of UAV communication systems. First, active IRSs require additional power supply, which brings great energy pressure to UAV communication systems. Second, when active IRSs amplify reflected signals, they also amplify the noise, which seriously affects the transmission quality of the communication link and increases the system's BER. Therefore, in the future design of active IRS-assisted UAV communication systems, a balance needs to be struck among transmission efficiency, energy consumption, and BER.

2) Joint Design of Active and Passive IRSs: One promising approach is the joint design of active IRSs and passive IRSs, which can avoid many adverse effects when either of them exists alone. Specifically, active IRS enhance the signal gain, while the passive IRS reduces the interference of the signal and suppresses the effect of amplified noise on the system. However, in the practical design, there are still some challenges. On one hand, the combination of the two increases the complexity of system design. It includes the consideration of deployment locations as well as cooperation of active and passive IRSs, and the optimisation of the ratio of the two types of reflection units. On the other hand, their integration increases the complexity of the formulated optimization problems. It lies in the increased number of parameters to be optimized and their coupling relationships. Furthermore, considerations of hardware implementation and the balance between system energy consumption and performance are also worthy of attention in future research.

C. PLS Enhancements for IRS-Assisted UAV Communications

In IRS-assisted UAV communications, accurate CSI acquisition remains challenging, while IRS-assisted attacks as well as pilot contamination attacks are two types of attacks that is difficult to defend against. Hence, they are still worth future discussions. But few researchers investigate the countermeasures for these two types of attacks.

1) Precise Acquisition of CSI: Although IRSs and UAVs can complement wireless network security from a physical layer perspective, the effectiveness of defense strategies against various attacks heavily relies on the acquisition of attackers' CSI. On the one hand, the passive IRS is a passive device that does not possess signal processing capabilities, and therefore unlikely to obtain perfect CSI. On the other hand, attackers are not registered in the network, and their appearance time and locations are generally unpredictable, making it difficult to obtain their CSI. Therefore, obtaining available CSI is crucial to the network security of IRS-assisted UAV communication systems. Further research is needed to explore how to obtain accurate CSI or other security methods that reduce the dependence on CSI.

2) Resistance to IRS-Assisted Attacks: It is a type of attack that equips airborne malicious attackers with IRSs to intercept or eavesdrop on communications among legitimate users [148]. This attack is based on IRS-assisted UAV communications and may be more harmful than traditional attacks. First, the mobility of UAVs make it difficult to predict attackers' movements. Second, malicious UAVs equipped with IRSs can intercept the signal transmission of legitimate links by beamforming. This is still a PLS issue, and defense measures for such attacks can be explored from the perspective of PLS. For example, jamming technologies are used to suppress the communication of malicious UAVs, which includes emitting jamming signals and utilizing IRS beamforming. It is also possible to design reasonable trajectories of airborne UAVs to keep them away from attackers. However, these approaches require the system to obtain certain positional and channel information about malicious UAVs, which is challenging in scenarios with airborne attackers, especially when their signals can be transmitted through IRS reflections.

3) **Resistance to Pilot Contamination Attacks:** For measures against attacks in IRS-assisted UAV communications, beamforming also plays a crucial role. Similarly, beamforming requires accurate CSI, which can be usually obtained via pilot signals. In fact, eavesdroppers may send malicious pilot signals with the same amplitude and phase as target pilot signals, or inject noise into target pilot signals to cause estimation errors at the receiving end. Thus, ineffective transmission is conducted and even favors eavesdroppers' information stealing. This is called pilot contamination attacks, which is first proposed in [149]. In IRS-assisted UAV communications, it is challenging to defend against pilot contamination attacks: i) the attacker's position cannot be accurately detected. ii) there's no effective method to identify the contaminated pilot signal, and iii) this pilot signal also interferes with the legitimate signal. Thus, research on corresponding defense measures in IRS-assisted UAV communication systems is required.

D. IRS and UAV-Assisted Maritime Communications

Currently, maritime communications are mainly realized based on satellites. However, their reliability and timeliness are not well guaranteed due to the long distances and harsh maritime communication environment. Therefore, IRS and UAVassisted maritime communications are promising to ensure stable and timely connectivity to support essential maritime applications. Compared with terrestrial communications, the complex maritime communication environment and special service requirements make maritime communications face great challenges.

1) Complex Maritime Communication Environments:

The complexity of maritime communication environments is characterised by two main aspects: First, multipath propagation and signal attenuation. In the maritime environment, the signal undergoes multiple path propagation due to the reflection of the water surface and the refraction of the waves. The signals in different directions lead to signal interference and multipath effect, which makes the path of the signal to the equipment more complicated, thus causing communication instability. Second, the dynamic marine environments. The marine environment is usually with dynamic changes, including waves, wind direction, tides, and these transformations affect the signal propagation path and attenuation characteristics. Third, the influence of evaporation ducting effects. This phenomenon is caused by the rapid changes in atmospheric temperature and humidity at specific height levels close to the ground, allowing wireless signals below a certain altitude to propagate over the sea surface for distances beyond the typical LoS. This requires novel modeling methods for the wireless maritime channel. In particular, it remains challenging to obtain maritime channel data to validate the practicality of the theoretical channel.

2) Special Service Requirements: Maritime users have a low distribution density, but have high requirements for network coverage and reliability. Although the IRS provides an inexpensive method of passive relaying, its deployment on the sea is still challenging. If the IRS is deployed on UAVs, their limited energy batteries may result in limited service times. If the IRS is deployed on the sea surface, the randomly fluctuating sea surface makes it impossible to properly reflect the beam to the intended users. Therefore, a reliable and lowcost way to achieve wide coverage of maritime communications is needed. For example, deploying the IRS on the seabed can reduce the effect of waves on the signal reflection from the IRS. In addition, it is possible to deploy multiple IRSs and UAVs for cooperative communications. However, there is no mature method on how to achieve coordination between IRSs and UAVs, how to collaboratively adapt to the dynamic maritime environment and tasks, and how to maintain the devices.

E. IRS and UAV-Assisted Sensing and Communications

In scenarios such as ITS, there are high requirements for communication quality and sensing accuracy. IRS and UAV are recognized as promising tools to enhance the quality of communications and sensing. However, there are still some challenges on how to utilize IRS and UAV for air-ground sensing as well as communication-sensing integration design.

1) IRS and UAV-Assisted Sensing: Sensing services involve capturing, processing, and providing data and information about the external environment or objects using sensors. Unlike communications, sensing services rely on LoS links, and NLoS links can affect sensing performance [150]. Therefore, the virtual LoS links established by IRS can improve the impact of the link environment on the sensing effectiveness. Meanwhile, the mobility of UAVs allows for the flexible establishment of LoS links. However, IRS-assisted UAV sensing still faces some challenges. On one hand, UAVs are mobile, leading to the Doppler effect, which makes it challenging to accurately sense ground objects. On the other hand, since IRS does not have the ability to process signals, the reliability of parameters obtained through virtual LoS links cannot be guaranteed. Additionally, in multi-target sensing scenarios, since the links from BS to IRSs are shared by all sensing targets, special designs are needed to differentiate the parameters for each sensing target.

2) IRS and UAV-Assisted Communication-Sensing Integration: Communication-sensing integration design is an effective way to achieve spectrum reuse. This integration shares wireless infrastructure equipment, enabling simultaneous information transmission and sensing information extraction, which also reduces hardware deployment costs [151]. With the flexibility of UAVs and the cost-effectiveness of IRSs, integrating IRSs and UAVs to build a cost-effective aerial comprehensive communications and sensing platform for real-time changing needs is a promising future vision. To realize this vision, several challenges need to be overcome. First, the integrated systems are affected by various complex factors, including resource constraints, UAV trajectories, IRS deployment locations, and various beamforming constraints. Second, asymmetric joint design for communications and sensing needs to be well considered. Communication-sensing integration design does not demand that communications and sensing must occur simultaneously, but requires a dynamic trade-off and selection between communications and sensing based on demand. Forcing symmetrical design in communications and sensing inevitably leads to excessive energy consumption, spectrum wastage, and inefficiency. And this asymmetric design is challenging due to dynamic trade-offs between communication and sensing with practical resource limitations.

V. CONCLUSION

In this article, we explore the research on IRS-assisted UAV communications for 6G networks. Specifically, We discuss key issues faced by IRS-assisted UAV communications, summarize key technologies, and introduce typical application scenarios. Then, existing solutions for key issues are summarized from different perspectives, including energy-constrained communications, secure communications, and enhanced communications. Last, we highlight some open issues and future research challenges of IRS-assisted UAV communications. Through this article, we can observe advantages of IRS-assisted UAV communications in addressing issues in relevant network environments under 6G networks. However, there are still challenges and difficulties that need to be further investigated. We hope that this article can provide useful references and insights for researchers and contribute to the advancement of this field.

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