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Intelligent Reflecting Surface in 6G Vehicular Communications: A Survey

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ABSTRACT The applications of Intelligent Transportation System (ITS) and autonomous driving in the 6G era heavily rely on the massive information exchange of ultra-wide bandwidth, high reliability, and low latency to guarantee the safety and experience. On the other hand, the signals in high frequency bands including Millimeter Wave (mmWave) and Terahertz (THz) can be easily blocked by the obstacles. To address this problem, Intelligent Reflecting Surface (IRS) has attracted a lot of attention since it can reflect the signals and change propagation directions the propagation directions in a highly intelligent and energy efficient way, which creates smart radio environments. Due to its easy deployment and low expense, it has been widely recognized as a promising technology for ground and aerial vehicular networks to enhance signal strength, physical layer security, and positioning accuracy. In this paper, we give a comprehensive survey of current research works on different IRS applications in ground-based vehicular communications and aerial vehicular communications after discussing its basic knowledge and main characteristics. To improve current works and spark more ideas, we summarize the challenges and discuss the future perspectives of IRS-aided 6G vehicular communications.

INDEX TERMS Intelligent reflecting surface, intelligent transportation system, smart radio environment, vehicular communications, 6G.

I. INTRODUCTION

The transportation industry has expanded from the ground to the sky, and Intelligent Transportation Systems (ITS) have become a major trend to achieve highly efficient transportation and management systems containing a massive number of ground vehicles and aerial vehicles. For the ground vehicle, traditional car companies and Internet auto companies such as BMW and Tesla, both show great interest in autonomous driving and are focusing on developing driver assistance systems [1], [2]. For aerial vehicles, airplanes are already equipped with autopilot systems and the academia and industry of Unmanned Aerial Vehicle (UAV) are working on stable flight control systems and drone swarm control [3]. The intelligence of transportation systems highly depends on the ability to acquire and exchange information [4]. It is essential to build high-speed and high-quality communication systems for vehicular networks.

Vehicle-to-everything (V2X) communication, the key technology of future ITS, enables vehicles to communicate with base stations (BSs), pedestrians, and other vehicles [5]. By obtaining a series of traffic information and environment information such as real-time road conditions, visibility, congestion condition, pedestrian information, and aerial field information, it can improve traffic efficiency, reduce congestion, as well as enhance driving and aviation safety [6]. Although 5 G technology provides communication networks with greater capacity and faster speeds, it is still far from meeting the needs of rapidly growing and highly dynamic

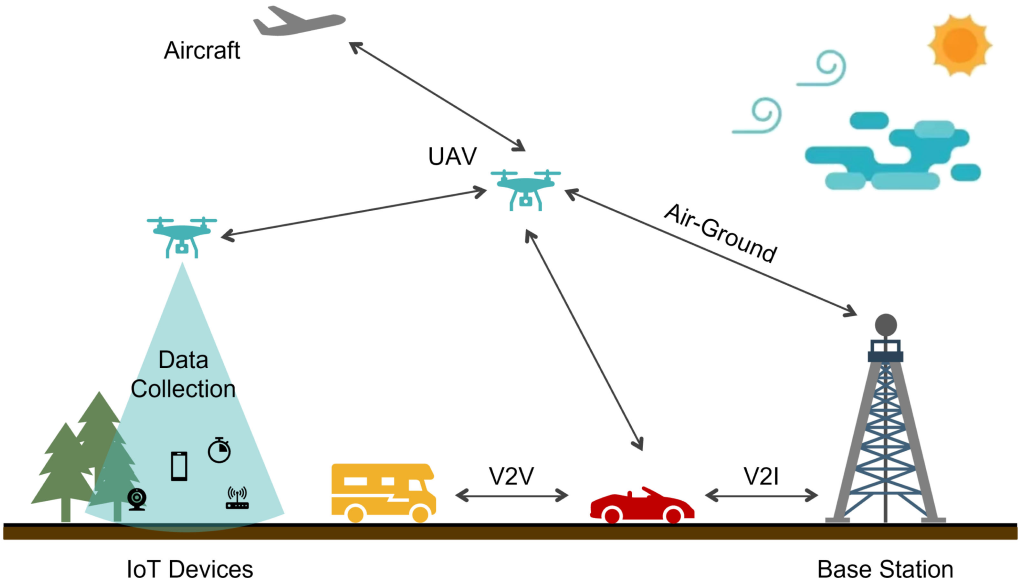

FIGURE 1. **Architecture of 6G ground-based and aerial vehicular communications.**

vehicular networks. 6G vehicular network aims to achieve smart radio environment which satisfies various application requirements and service types [7]. Fig. 1 shows the architecture of 6G vehicular networks. The scientific and technical challenges in terms of data rate, latency, coverage, energy efficiency, intelligence level, networking, and security, lead the vehicular networks for ground vehicles and aerial vehicles undergoing a transformation unlike anything we have seen before and also put forward higher requirements for communication technologies in the next generation.

6G is expected to expand the frequency band to Terahertz (THz) and increase the throughput by 1000 times over 5G [8]. The ultra-high frequency technology offers faster transmission and gives access to more users. However, the attenuation of THz waves narrows the transmission coverage, which makes the number of required BSs and energy consumption in THz communications increase significantly [9]. The propagation link can be easily blocked by physical objects due to the short wavelength, which puts strict requirements on the beam alignment [10], [11]. In V2X communications, the buildings in urban scenarios or hills and plants in the countryside may cause strong shadowing effects, reducing energy efficiency and spectral efficiency. Moreover, the high mobility of ground vehicles and aerial vehicles reduces the channel stability, resulting in low transmission rates. In addition, the changing three-dimensional position of the air vehicles makes communication even more difficult. How to control the propagation and reduce the fading of THz signals with high energy efficiency in vehicular communications still remains an open challenge. Unstable V2X communication will bring risks to driving safety and communication security. It is important to expand the range of communication and improve the communication stability in a green manner. Aiming to control the signal propagation and create a smart radio environment, Intelligent Reflecting Surface (IRS) or Reconfigurable Intelligent Surface (RIS) has been regarded as a promising technology in 6G. IRSs are metasurfaces that can control the phase of electromagnetic (EM) waves programmablely and use reflection to redesign channels [12]. When the direct Line-of-Sight (LoS) link between the sender and receiver is blocked by an obstacle, a new propagation path bypassing the obstacle can be established by the reflection of IRS. Thus, the signal can avoid penetration loss and maintain a desirable transmission rate. The additional reflection path can also improve the Signal-to-Interference-plus-Noise Ratio (SINR). By controlling the propagation of reflected EM waves, the IRS helps overcome the destructive effect of multipath fading and shadow fading with low energy cost [13].

The ability of IRS to enable beyond LoS and energy-efficient communications shows great potential in 6G vehicular networks. For the Millimeter Wave (mmWave) or THz bands in 6G vehicular networks, IRSs are promising to assist Vehicle-to-Vehicle (V2V) communications, Vehicle-to-Infrastructure (V2I) communications, and Vehicle-to-Pedestrian (V2P) communications by enhancing multipath propagation and enlarging transmission coverage. The 2-Dimensional (2D) planar structure also makes IRS easy to be deployed. And the passive reflection mechanism allows IRS to work in a low-energy-consumption way which meets the requirement of green 6G. Recent researches on hardware and materials show that it is possible to control the reflection dynamically which enables the IRS to do real-time beamforming and serve multiple mobile users [14], [15]. The reconfigurable passive beamforming also allows IRS to play an important role of improving physical layer security in ground-based and aerial vehicular communications.

In this article, we give a comprehensive survey of the IRS technology employment in vehicular networks and propose some open issues of the ground and aerial V2X communications. In the first part, we introduce the IRS technology and its development. Next, we provide an overview of IRS applications in ground-based vehicular communications and the advantages of IRS as an evolutionary technology in aerial vehicular communications. There are still some problems remaining be solved before IRS is widely used in vehicular communications. We highlight the challenges to provide direction for the application of IRS in vehicular communications whether ground-based or aerial.

The remainder of this article is organized as follows: Section II introduces the IRS technology and how it works. Section III describes the application of IRS in ground-based vehicular communications. In Section IV, we summarize the IRS-aided aerial vehicular communications. Later, we address some crucial challenges that need to face for IRS applied in vehicular communications in Section V. Finally, conclusions are drawn in Section VI.

II. INTELLIGENT REFLECTING SURFACE

A. WHAT IS AN IRS?

IRS, the planar surface comprising a large amount of metamaterial reflection element with adjustable phase shift, is designed to programmablely manipulate the phase shift of the incident EM wave. This emerging technology allows the propagation of reflected EM wave to be determined and enable the wireless environment to be smartly controlled [16]. The first idea of controlling signal propagation through a reflective array dates back to 1997. Pozar *et al.* designed reflectarrays using microstrip elements to flexibly control the reflections of mmWave in [17]. Their research shows that reflectarrays are able to do beamforming in mmWave band and gives the guidelines of improvement such as materials, feed design, and fabrication.

In recent years, with the development of hardware and material, several technologies have been applied to achieve the tunability of metamaterials, such as embedding varactor diodes in the surface [18], integrating metasurface cells with positive intrinsic-negative (PIN) diodes [19]. Reconfigurable capabilities have become possible on metasurfaces, and several research teams have built their prototypes. Arun *et al.* from Massachusetts Institute of Technology (MIT), USA, have built software-controlled passive antenna arrays to do passive beamforming, which is named as RFocus [20]. Dai *et al.* have developed high-gain yet low-cost 256-element RIS based on PIN diodes [21]. And a team from Southeast University, China, has achieved transmission-reflection control and polarization controls on their reconfigurable anisotropic digital coding metasurface [22]. Pitilakis *et al.* have designed a multi-functional reconfigurable metasurface and proposed a new structure to perform multiple tunable functionalities [23]. NTT DOCOMO, INC, Japan, has conducted a two-dimensional metasurface that is optically transparent [24]. This design allows metasurfaces for unobtrusive use in the windows and billboards.

TABLE 1. Comparison of Active Relays and IRSs

	Active relays	IRSs
Mode	Active	Passive
Duplex	Half-duplex	Full-duplex
Energy cost	High	Low
User interference	High	Low

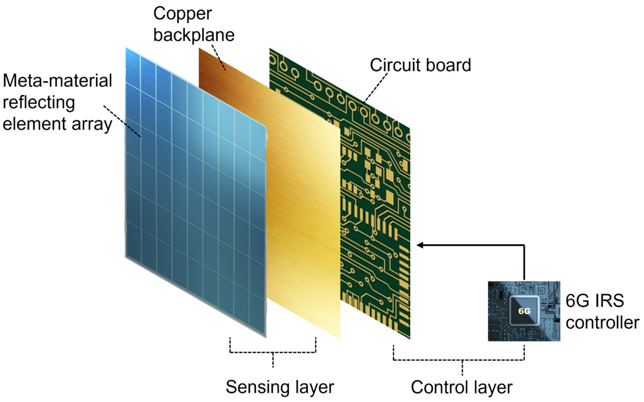

FIGURE 2. Hardware architecture of IRS.

Compared with active relays, the advantages of IRSs are multi-fold, as shown in Table 1. IRS passively reflects the incident signal and has very low energy consumption only to ensure the reconfigurability of passive components [25]. In addition, IRS can be easily operated in the full-duplex mode without the need for complex interference cancellation [26]. Thus, IRS shows its potential on the way to creating a smart wireless environment in the next-generation communication networks.

B. MAIN CHARACTERISTICS AND THE STRUCTURE OF IRSS

The designs of IRSs from different teams are diverse, but they all follow some characteristics as below:

Nearly-Passive: IRSs reconfigures the channels by controlling reflections rather than enlarging the reflecting signals. They only use minimal power to control and program phases. During and after configuration, there is no analogy-to-digital/digital-to-analogy conversion and power amplification.

Reconfigurable: each reflecting element can be controlled independently to modify the phase, amplitude, frequency, and polarization of incident radio waves. The whole surface is considered contiguous and can reshape the signals at any point and requiring real-time reconfigurability.

Easy-deployment: IRSs are 2D surfaces with thin layers. They can be easily deployed on the exterior wall of buildings, ceilings, or even windows.

Fig. 2 shows the hardware architecture of IRS. The main structure of IRS is composed of two layers, the sensing layer and the control layer [27]. The sensing layer consists of two parts, the reflecting plane and a copper backplane. The reflecting plane contains a large amount of 2D tunable metamaterial elements. Each element can be controlled individually to interact with the incident signal and redesign the reflected signal. The copper backplane is used to avoid signal leakage. The control layer consists of a 6G smart controller and a circuit board behind the copper backplane. The smart controller is able to communicate with the end-users or access points and programmablely adjust the reflection amplitude/phase shift of each metamaterial unit via the circuit board.

III. IRS-AIDED GROUND-BASED VEHICULAR COMMUNICATIONS

With automobiles becoming the most dominant mode of travel and transportation, the ground-based vehicular network has become an integral part of our daily lives. The trend towards highly automated vehicles and autonomous driving can lead to comfortable and efficient road traffic, even for those who are not allowed or able to drive. The 6G ground-based vehicular networks will be integrated with more elements, such as infrastructure, on-board sensors, on-board actuators, on-board controllers, etc., and require higher-performance communication facilities and networks to achieve high-speed information transfer [28]. IRSs are expected to take roles in future vehicular networks for their beyond LoS ability and easy deployment. In this section, we survey the applications of IRS as a smart radio environment technology in ground-based vehicular networks.

A. ENABLING PROGRAMMABLE AND LOW SHADOWING EFFECT V2X ENVIRONMENT

The development of modern transportation drives the transportation infrastructure to become increasingly complex, such as intersections, d-junctions, viaducts, and overpasses. Each type of road infrastructure unit affects wireless communication differently. In 6G vehicular communications, the radio signals in mmWave or THz frequency band have relatively short wavelength and low penetrating ability [29]. The propagation of wireless signals can be easily obstructed by static obstacles (buildings, walls, trees, etc.) and dynamic obstacles (passing vehicles, pedestrians, etc.). Earlier studies mainly focused on the placement of Road Side Units (RSUs) [30]–[32], while the established RSUs are difficult and costly to change locations. Moreover, in 6G urban environments, a large number of RSUs are required and some locations are not suitable for RSU deployment due to the geographical terrains, which can significantly increase construction costs. A more flexible and intelligent way is needed to ensure LoS and stable channels in 6G vehicular communications.

To maintain LoS communications, it is practical to reflect the signal to bypass the obstacles. In [33], Qureshi *et al.* study the impact of road infrastructure units on signal propagation and introduce signal reflectors to provide a low-cost solution for rebuilding LoS communication. They use a geometrical approach to jointly optimize the position of RSU and reflector. Advances in technology have brought IRS to wireless communication networks, which enables it to control reflected signals in a more intelligent way. By configuring the phase shifts through IRS controller, the IRS can provide an indirect LoS wireless communication link for vehicles traveling in signal blocked areas, and track users in real-time [34], as shown in Fig. 3. The application of passive smart surfaces for V2I communications is studied in [35]. Nolan *et al.* show that the smart reflecting surface as a lightweight mechanism enables vehicles to receive more information and brings intelligence for transportation facilities. The outage performance, robustness, and workload of IRS-aided vehicular networks under multiple vehicles are analyzed in [36]–[39]. The researches show that the vehicular communication system with IRS has a much lower outage probability and higher robustness than the system without IRS. The influence of geographical terrains on vehicular communication can not be neglected. Dhruvakumar *et al.* simulate end-to-end wireless channels in two different terrains and apply the IRS to enhance signal transmission [40]. The simulation result demonstrates that IRS enhances transmission stability and communication coverage. Maintaining high-speed communication in ground-based vehicular networks requires high-accuracy positioning. The process of establishing communication needs to locate the user first, while precise locating can also be used for monitoring. IRS-aided systems can obtain more channel information than that without IRS, and IRS can track and locate vehicles based on information such as the direction of the incident wave. In [41]–[43], IRSs are utilized for positioning cell phone users and it is found that the IRS-aided system has higher positioning accuracy and larger coverage over that without IRS. IRS can be first used to enhance the locating accuracy, and when a stable connection is established, it can be further used to enhance communications by the pre-predicted locations. Research has found that the vehicle can be located more accurately by calculating the time when the signal from the antenna reaches the vehicle directly and the time when the signal is reflected by an ordinary wall [44]. Compared to ordinary walls, IRS can intelligently control the direction and polarization of the reflected waves. Therefore, we believe that IRS can be applied to do positioning with high accuracy in vehicular networks.

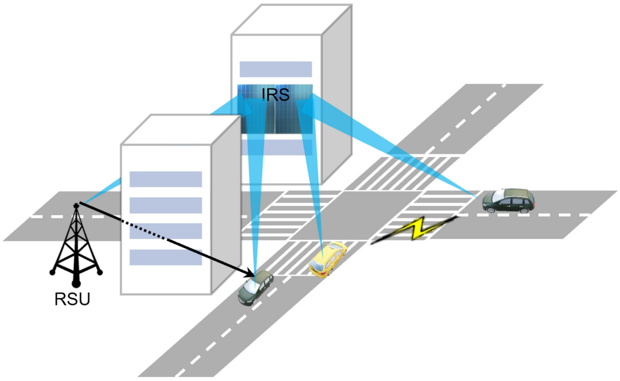

FIGURE 3. **IRS enables smart radio V2X environment.**

The wireless resources such as spectrum and power are very limited, and the resource allocation needs to be optimized in networks under multiple users [45]. In vehicular networks, the high mobility of users makes resource allocation more complex and challenging. The spectrum sharing problem in the situation that multiple V2V links reuse the spectrum already occupied by V2I links is studied in [46]. In [47], the joint power and spectrum resource allocation problem is also studied. In the model, V2V and V2I are both taken into account as well as considering the slowly varying large-scale fading channel information. The user scheduling problem under high mobility in IRS-aided system is optimized in [48]. The resource allocation problems in IRS-aided vehicular networks mentioned above all reflect nonconvexity. To address this issue, [46] and [47] decompose the problem into several subproblems and adopt the alternate optimization, while [48] utilizes the deep reinforcement learning technique. The above researches show that IRS can largely compensate for the channel gain loss due to the high mobility of vehicles and significantly increase the sum capacity of vehicular communication.

IRS can also be used to assist the passengers inside the vehicle to communicate with the outside. A hybrid-equivalent surface-edge current model has been proposed to analyze the radiation of antennas installed on vehicles in [49]. This research could provide a theoretical basis for placing IRS on vehicle surfaces. In [50], Huang *et al.* study IRS deployed inside high-speed mobile vehicles to aid passengers in communicating with roadside BSs. The fast channel fading caused by the Doppler effect of vehicles moving at the high speed is significantly mitigated by IRS-enabled passive beamforming.

B. IMPROVING TASK OFFLOADING IN VEHICULAR NETWORK

With vehicles becoming increasingly intelligent, vehicles need to join the network to compute tasks. In the ground-based vehicular networks, some tasks are related to the safety of passengers in the car and require to be processed within a short latency, such as object recognition, troubleshooting, and accident forewarning [51]. Moreover, for the tasks like navigation and entertainment, a large database is needed to store the map, video and music resources. The onboard computer may not be able to meet the high requirement for some large-size tasks while the long data link of cloud computing causes undesirable time delay. Multi-access Edge Computing (MEC) is the technology providing cloud computing platforms and computation offloading services at the network edge [52]. Compared to cloud computing, MEC can significantly shorten the data link and reduce the time delay significantly. The MEC enables vehicles to process tasks locally and has less core network occupation [53], [54].

For an already deployed MEC-served vehicular network, the computation performance highly depends on the processor efficiency since the clock rate and the number of processors are constants. To keep the MEC server always in service, it is of great importance to ensure the desirable data transmission. A stable link can transmit data more efficiently, while a link under poor offloading conditions may cause the MEC processor to be occupied for a long time and unable to serve more users [55]. Fig. 4 shows the IRS-aided vehicular network. The IRS is able to re-design the propagation path of signals by reflection and improve the channel conditions. For vehicle users under poor communication conditions, IRS can help to build new propagation links, so that they can establish stable communication with the MEC server and offload the computation tasks. The authors in [56] investigate and model the resource allocation problem of computing resources and communication resources in IRS-aided MEC-served vehicular networks. Simulation results confirm the higher computational performance of the system with IRS. Thus, we can see that IRS can influence and benefit the computing resource allocation. Although little research has been done on IRS in edge computing for vehicular networks, it will become increasingly important with the growing demand for computing power in autonomous driving applications.

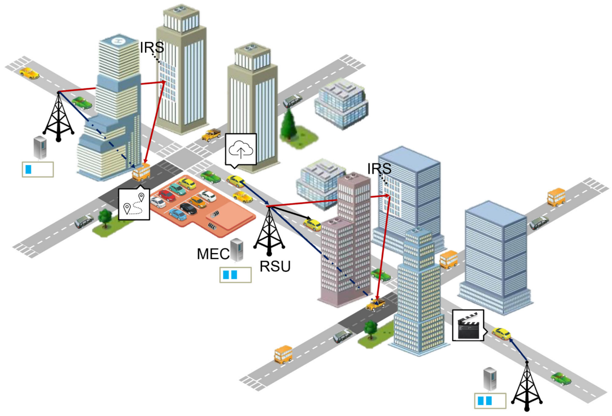

FIGURE 4. **IRS-aided task offloading in 6G ground-based vehicular networks.**

C. PHYSICAL LAYER SECURITY

V2X communications rely on seamless data exchange and information transfer. The increased connectivity makes the ground-based vehicular network an open system and gives rise to new risks in physical layer security which may disrupt the network, threaten personnel safety in vehicles, and leak important information [57]. In a crowded city or suburban area, each vehicle user is surrounded by a group of scatters which highly influences the LoS propagation and even disrupts the signal. Deploying multiple BSs requires sufficient space and incurs excessive costs. In the traditional V2X communication scenarios, the third vehicle user may be chosen as the relay if the LoS channel is blocked between the sender and receiver [58]. However, for some highly confidential data, this raises the risk of information leakage. The high mobility of vehicles makes it more challenging to ensure security in the physical layer. It is of great importance to enhance security in vehicular communications in a low-cost and energy-efficient way.

As a promising technology in smart radio environment, IRS gives a new direction to enhance the secrecy rate in vehicular networks. By adaptively adjusting the phase shift of the

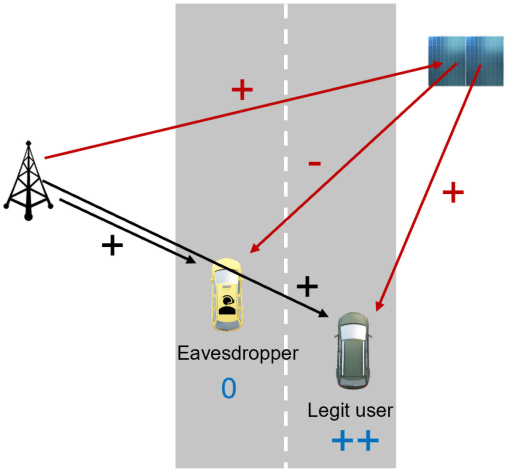

FIGURE 5. IRS enhances physical layer security in V2X communications.

reflecting elements, IRS can enhance the desired signal or suppress unwanted signals through controlling the reflected signal to add constructively or destructively to the non-IRS reflected signal at the receiver [59]. A new desirable propagation path between sender and receiver can be built by IRS reflection rather than using another vehicle user as a relay [60]. The issue of eavesdropping has a significant impact on network security. In [61], the approach to cancel the signal leaked to the eavesdropper in IRS-aided mobile networks is studied. When an eavesdropper is around the legitimate vehicle user, both the eavesdropper and legitimate users can receive the signal from RSU. And IRS can suppress the signal by reflecting a signal to the eavesdropper that is out of phase with the signal it eavesdrops on, and enhance the received power at the legitimate user simultaneously by reflecting an in-phase signal. This feature of IRS can be applied to ground-based vehicular networks, as shown in Fig. 5. The secret information received at the eavesdropper vehicle can be canceled by the IRS-reflected out-of-phase signal without additional cost at the legitimate vehicle side. In [62] and [60], the security of ground-based vehicle network is studied where IRS is utilized. The studies verify the potential for improving security with IRS in V2V and V2I communications, and that the physical layer security is influenced by the position of IRS and its number of reflecting elements.

IV. IRS-AIDED AERIAL VEHICULAR COMMUNICATIONS

With the development of control technology and radio technology, UAVs have been developed and shown great potential in both civilian and military applications. Thanks to more flexible controls and a lighter structure than manned aircraft, they are more capable of performing highly repetitive and dangerous tasks and can be deployed more flexibly [63]. Unlike ground-based wireless networks, the high mobility of UAVs causes the network nodes to continuously change in 3-Dimensional (3D) spaces, especially in Z-axis, which keeps the network topology fluid [64]. This requires a highly reconfigurable and intelligent network architecture, and IRS hits the spot. In this section, we survey the applications of IRS in aerial vehicular communications to improve transmission under high mobility scenarios.

A. ENHANCING AIR-TO-GROUND COMMUNICATIONS AND BEAM TRACKING

Air-to-ground communication is the data transmission between terrestrial fields and aerial fields, which provides a variety of services for aerial vehicles, such as communication and addressing of civil airliners, aerial surveillance and information collection from ground-based Internet of things (IoT) devices of UAVs, and air traffic safety control, etc [65]. For continuous service, aerial ITS requires a reliable high-capacity data transmission network [66]. In the 5G era, 3D beamforming improves the communication gain through tracking channel variations caused by the high maneuverability of UAVs. However, due to the increasingly complex urban environment, the LoS connection between the aerial vehicle and the ground can be easily blocked, resulting in serious degradation of the communication quality. There is a critical need for a wide communication coverage area to enable and assist Non-Line-of-Sight (NLoS) flights.

IRS has great advantages of extending network coverage and improving communication reliability. When the link between the aerial vehicle and the ground target is blocked, the IRS can re-establish the link beyond LoS by reflection, which can help achieve 3D reflect beamforming [67]. In [68], the authors apply IRS to UAV networks to enhance air-ground communication performance and demonstrate IRS-assisted UAV communication systems can exhibit ten times higher achievable ergodic capacity compared to conventional UAV communications. IRS-aided air-to-ground communications also outperform systems without IRS in terms of robustness, reliability, and energy efficiency [69]–[73]. Intelligent control of UAVs is highly dependent on accurate positioning, and UAVs have more variability in the Z-axis than ground vehicles. Ranjha *et al.* use IRS to assist UAVs' communicating with ground users and enhance the accuracy of UAV positioning in [74]. Their research validates that the location of the UAV is critical to the reliability of data transmission and IRS can enhance performance gains. Thus, the benefits of IRS in positioning can be applied to aid in the wireless control of UAVs and the detection of illegal aircraft entering the airspace.

At present, accessing UAVs through cellular networks is still mainstream. As the current deployed BSs are mainly for ground users, the antennas are designed to be tilted down, for which the UAVs suffer from poor signal strength, especially in downlink networks. To tackle this issue, IRS can reflect the tilted-down beam to the airspace where the UAV is located. Ma *et al.* applied IRS to UAV cellular communications and analyzed the effect of signal gain due to IRS deployment versus UAV altitude and various IRS parameters including size, altitude, and distance from the BS [75]. This study shows that signal gain can be significantly improved by using IRS for UAVs flying above cellular BSs, and that optimizing the

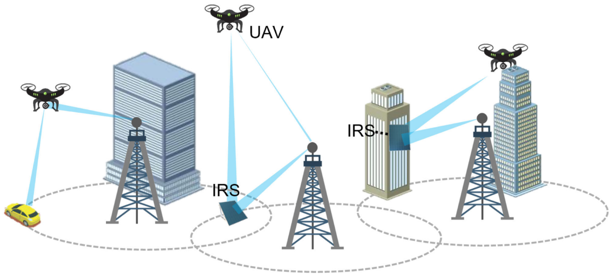

FIGURE 6. IRS-aided air-to-ground communications.

IRS position can further improve the gain. In communication systems with UAVs as relays to assist BS and ground users, energy efficiency can be improved by 45% by deploying IRS [76]. Fig. 6 shows the air-to-ground communications with IRS assisted. Inter-cell interference is a non-negligible problem in cellular networks. The open airspace causes little loss in wireless signal transmission, and radio waves from multiple cellular BSs can propagate into the airspace. Signals from adjacent cells in the airspace can cause interference to the UAV and lead to degradation of transmission performance. In [77], Hashida *etal.* discuss the interference of conventional cellular networks to UAV, and it is found that the interference power in adjacent cells depends on the elevation angle of the UAV. To address inter-cell interference in aerial space, they utilize IRS in each cell to control the direction of radio wave reflection and prevent the signals from penetrating into neighboring cells. The way UAVs access the cellular network also affects performance and needs to be carefully considered. The performance of different multiple access schemes with IRS participation is analyzed in [78] and [79]. According to conventional thought, Non-Orthogonal Multiple Access (NOMA) has significant improvements over Orthogonal Multiple Access (OMA) in systems without IRS-aided. This work has revealed that NOMA may perform worse than TDMA for near-IRS users with symmetric rates. Thus, in systems with a large number of users and IRS assistance, pairing users at asymmetric rates and/or deploying them asymmetrically can enhance the gain of NOMA over OMA, which also indicates the importance of high positioning accuracy. In [80] and [81], IRS-aided UAV NOMA network is investigated. By controlling the UAV motion, adjusting the user power, and combining IRS beamforming, the IRS-NOMA system provides a significant performance improvement over the IRS-OMA system.

THz technology will be adopted in 6G, making THz air-to-ground communications an important research direction. Due to the short wavelength of ultra-high frequency signals, the THz signal has great attenuation and poor penetration capability. The presence of physical obstacles such as buildings and terrains makes the transmission of terahertz signals unstable. The beyond LoS ability of IRS has great potential in THz communications. By deploying IRS, signals can be realigned and transmitted beyond LoS, thus improving system connectivity by avoiding penetration loss [82]–[84]. And the sum-rate performance of THz communication systems can be further improved by adjusting and optimizing the phase shift of reflecting elements. Pan *et al.* investigate THz communications for UAVs with IRS support and achieve considerable performance improvements by jointly optimizing UAV trajectories, IRS phase shifts, THz subband assignments, and power control [85].

B. UAV TRAJECTORY CONTROL AND PASSIVE BEAMFORMING

The flexible deployment, low energy cost, and high mobility [86] of UAVs allow them to be deployed as aerial temporary tele-traffic hotspot BSs for providing uninterrupted connectivity [87]. UAVs could either hover at certain locations, or fly contiguously over the served terrestrial terminals following a predetermined trajectory. In IoT networks, UAVs can dynamically adjust their flight trajectories based on the locations of the served IoT devices and approach each IoT device in turn to shorten their link distance, enabling more energy-efficient data collection [88]–[90]. Since UAVs are powered by batteries, the energy available for flight and communication is very limited. It is important to reasonably allocate the power resource. Moreover, in the urban environment, the LoS link between the UAV and the ground device can be easily blocked by physical objects, resulting in severe channel quality degradation and a longer task latency of each IoT device. In order to achieve the desired performance, we need to improve the communication system and carefully design the trajectory to balance the energy consumption of flight and communication.

In [91], the UAV trajectory design problem is transformed into a complex geometric coverage problem and a geometric disk cover algorithm is introduced to find the turning points at which a UAV could cover IoT devices as many as possible. In [92], a new concept of Virtual Base Stations (VBSs) is introduced to be as waypoints in trajectory design. Both of the two above researches are aiming to select waypoints that can serve the maximum number of IoT devices. The radius of waypoint coverage is closely related to the maximum communication distance of UAVs. The commonality between these two studies is to transform the UAV trajectory control problem into the deployment problem of several geometric circles, in which the path point is the center of the circle and the radius is the communication distance. One way to increase the radius of communication range is to increase the power of the transmitted signal, but for IoT and UAV, this definitely strains the already limited energy. Another way is to focus the signal energy in a specified direction by smartly controlling the propagation environment. IRS can help UAVs and ground-based IoT devices to establish links beyond LoS and extend signal coverage without additional cost on UAV and IoT sides [93], as shown in Fig. 7. With IRS aided, an additional link can be built to enhance the SINR via adjusting the amplitudes and phase-shifts of incident signals, allowing the UAV to extend its data collection range while hovering over a waypoint, thereby reducing the number of waypoints required and significantly shortening the trajectory. IRS can be

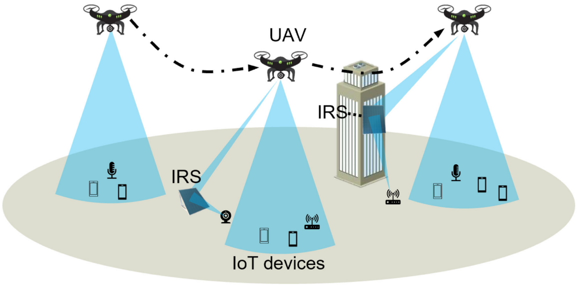

FIGURE 7. UAV trajectory control with IRS aided.

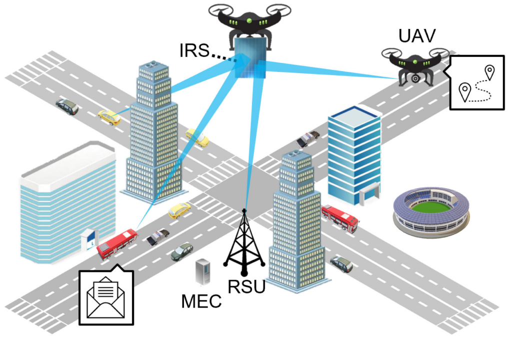

FIGURE 8. IRS aerial relaying platform.

easily deployed on the ground close to the IoT device area or on the building facade, and the communication performance is enhanced without additional cost on the UAV side. Moreover, the completion time can be minimized due to the shortened trajectory.

In order to take advantage of promising smart surface technologies, it is necessary to take into account the interaction of trajectory with passive beamforming. Controlling IRS beamforming to focus on the served IoT can avoid wasting IRS resources and further improve the communication quality. Li *et al.* propose an RIS-assisted UAV communication system and optimize the average achievable rate by jointly designing UAV trajectory and passive beamforming by considering practical UAV mobility and phase-shift constraints in [94]. The involvement of IRS enables the UAV-IoT system to consume much less energy. In [72] and [80], the energy consumption and resource allocation of IRS-aided UAV data collection is considered. The above two researches show that the system with IRS has less average power consumption. Joint optimization on UAV trajectories and IRS passive beamforming is also applied in MEC-served UAV networks. In [95], the UAV is considered as a flying MEC platform and an IRS is used to assist task offloading. With the phase-shift design of IRS, all elements of IRS can be jointly adjusted according to the timely positions of UAV and ground IoT devices to achieve the alignment of different signals. The research proposes a successive convex approximation method to solve the joint non-convex problem of trajectory design, mission offloading, and caching for UAVs. The simulation results show the high energy efficiency of IRS-assisted UAV and improvement in reducing task delay.

C. IRS AERIAL RELAYING PLATFORM

UAVs have the cargo-carrying capacity, and there are some transportation companies using UAVs for couriers delivery [96]. The development of metamaterials enables the physical size of the IRS to be reduced, freeing it from the limitations of ground deployment. Therefore, IRS can be mounted on UAVs or other aerial vehicles for greater flexibility. IRSs acquire high mobility from UAVs, which allows them to fly close to target users and build highly reliable communications, especially in disaster regions. With IRS mounted on the UAV, the conventional Rayleigh fading channel can be converted into a Rician fading channel through the newly generated equivalent LoS channel [97]. While deployed on the building or the ground, the planar IRS is only able to serve users who are in front of it. UAVs can hover and rotate 360 degrees, which allows the mounted planar IRS to provide service three-dimensionally. For some specially designed IRSs, such as spherical IRSs, while mounted on the UAV, wider communication coverage and higher positioning accuracy can be achieved [98]. IRS aerial platform can not only serve users on the ground but also users in the air, as shown in Fig. 8. The superiority of the IRS aerial platform is confirmed in [99]–[102]. With the IRS aerial platform, it is possible to enhance the signal-to-noise ratio (SNR), improve the transmission capacity of the network, and reduce the probability of interruptions. Unlike terrestrial-based IRS, IRS aerial platforms with high mobility in 3D space need to take into account the effects of jittering. Through UAV hovering experiments, Wu *et al.* analyze the essence of jittering [103]. They then apply the results to the IRS aerial platform to mitigate the negative effects of jittering on the system. This study further increases the feasibility of the IRS aerial platform being applied in practice. The size of IRS on a single UAV platform is often limited, and recent developments in UAV swarm control have provided new directions for improving the performance of IRS aerial platforms. In [104], authors form multiple UAVs into a UAV swarm to collaboratively enable aerial IRS. This study demonstrates the significant advantages of IRS-based aerial platform swarms in terms of aperture gain, cooperative communications, spatial multiplexing, resistance to destruction, and flight stability.

Like the ground-based vehicular network, the information security in the aerial field cannot be neglected. Researches show that the secrecy rate for legitimate users can be significantly increased when the transmitter utilizes information about the relative distance of the passive eavesdropper [105], or the distance between the communication peers decreases [106]. Compared to the IRS installed in a fixed location, the IRS aerial platform allows more flexibility to control the distance to the legitimate user and grasp the information of the eavesdropper through the moving UAV. In [107], the secrecy performance of IRS-aided UAV relay system is studied. The study considers the signal transmission from base station signals to legitimate users via an IRS-equipped UAV platform while multiple eavesdroppers are around. The authors in [107] study the ability of the IRS aerial platform in enhancing the confidentiality performance of Rician fading channels by the wireless environment modeling and numerical analysis. As a platform achieved by UAV, the trajectory also needs to be designed in secure networks with multiple users. Long *et al.* investigate the impact of UAV trajectory, phase shift of RIS, user association, and transmit power on the secure energy efficiency [101]. By further optimizing the above parameters jointly, they have reached an improvement in secure energy efficiency by 38%.

V. CHALLENGES IN IRS-AIDED VEHICULAR COMMUNICATIONS

In previous sections, we have discussed the general research directions and applications of IRS in ground-based vehicular networks and aerial vehicular networks. While IRS can provide significant performance improvements to vehicular communications, there are still some challenges in design and implementation. In this section, we discuss the key issues that need to be addressed urgently.

A. CHANNEL ESTIMATION

IRS controls the propagation of reflected signals by adjusting the phase shift of metamaterial elements. The performance of passive beamforming highly depends on accurate channel estimates while it is difficult to estimate the IRS channel due to the massive amount of passive elements. Most of the current researches in IRS-aided vehicular networks use the full Channel State Information (CSI) model. And most studies related to channel estimation in IRS-assisted cellular communications assume static scenarios that neglect the mobility of mobile-phone users [108]–[111]. However, in real vehicular communication scenarios, the dynamic link states caused by vehicles moving at high speeds can make the CSI difficult to estimate. The association between vehicles and IRS without prior planning can cause negative effects on system performance and communication resource utilization. Improving high accuracy for channel estimation always incurs extensive overhead in channel training and power consumption, which leads to additional costs in system construction. How to ensure highly accurate CSI estimation and energy efficiency is still one of the major issues in IRS-aided vehicular communications.

B. DEPLOYMENT OPTIMIZATION

The flat structure of IRS makes it easy to deploy. With the exception of IRS aerial platform, the IRS location is relatively fixed after deployment. Since IRS is used to assist local communication and extend coverage, the operating range will be smaller than that of active BSs, and the deployment location of IRS needs to be considered. In scenarios with static users, the system with IRS aided reaches higher performance when IRS is deployed near users or BSs [27] and [112]. However, in vehicular networks, the vehicles are moving at high speeds. For the ground-based vehicular networks, the vehicle density on the road is dynamically changing in one day. For example, in the morning rush hour, most vehicles enter the downtown, while in the evening rush hour, most vehicles leave the downtown. For the aerial vehicular networks, we have to consider the influence of terrains and the interaction between trajectory and terrestrial devices while deploying IRSs. In addition to IRS location optimization, we also need to consider the number and size of IRSs. IRSs that are too small in size or insufficient in number will result in unsatisfying energy of the reflected signal, while too large in size or too many will lead to waste and additional cost.

C. CONTROLLING TECHNOLOGY

Although the current IRS enables multi-channel multi-user transmission and real-time beamforming, there is still a long way to go before being widely used in vehicular communications. In cellular networks for cell phone users, where the user locations change relatively slowly, the existing IRS is capable of achieving multi-user beamforming. The high mobility of vehicles makes the position change dynamically every second, which requires the focus of the IRS to follow accordingly. In ground-based vehicular networks, the motion of ground vehicle users is relatively flat, while in aerial vehicular networks, the motion of aerial vehicles becomes 3D, requiring more precise and constant adjustment for the phase shifts of all reflecting elements. This places higher demands on the IRS controller and control circuitry. In V2I communication, the link between the IRS and base station is fixed due to the fixed location of the base station, and the IRS only needs to adjust the connection with the user. In V2V or V2P communications, the users at both ends of the communication are in motion and IRS needs to adjust the phase shift to control the link to the transmitter and the link to the receiver separately. Thus, IRSs need controllers and circuits that can carry more computational power, as well as more efficient and intelligent phase-shifting control algorithms.

VI. CONCLUSION

In vehicular networks, the increasingly diverse demands of users bring a massive amount of data and the growth of tasks. The ground-based vehicular network and the aerial vehicular network are in an emergency to be upgraded. The IRS, with its flexible deployment, low energy cost, and low user interference, has been regarded as the key technology to create smart radio environment in 6G. With IRSs, vehicular networks are able to communicate more efficiently and transfer data faster. In this article, we have introduced the technology of IRS and identified the roles that IRS can play in the ground-based and aerial vehicular networks. IRSs show great potential to improve the 6G vehicular communications. Furthermore, we address some challenges in IRS-aided vehicular networks. These challenges provide direction for the development of IRS as well as opportunities. We foresee the participation of IRS in the vehicular networks whether on the ground or in the aerial field and we expect this article to provide academic professionals for the next-generation communications.

REFERENCES

[1] "Autonomous driving – 5 steps to the self-driving car," Accessed: Mar. 30, 2022. [Online]. Available: https://www.bmw.com/en/automotive-life/autonomous-driving.html

[2] "Autopilot," Accessed: Jan. 21, 2022. [Online]. Available: https://www.tesla.com/autopilot

[3] A. Tahir, J. Böling, M.-H. Haghbayan, H. T. Toivonen, and J. Plosila, "Swarms of unmanned aerial vehicles - a survey," *J. Ind. Inf. Integration*, vol. 16, 2019, Art. no. 100106.

[4] J. Wang, J. Liu, and N. Kato, "Networking and communications in autonomous driving: A survey," *IEEE Commun. Surv. Tut.*, vol. 21, no. 2, pp. 1243–1274, Apr.–Jun. 2019.

[5] S. Chen *et al.*, "Vehicle-to-everything (V2X) services supported by LTE-based systems and 5G," *IEEE Commun. Standards Mag.*, vol. 1, no. 2, pp. 70–76, Jul. 2017.

[6] M. B. Mollah *et al.*, "Blockchain for the internet of vehicles towards intelligent transportation systems: A survey," *IEEE Internet Things J.*, vol. 8, no. 6, pp. 4157–4185, Mar. 2021.

[7] F. Tang, Y. Kawamoto, N. Kato, and J. Liu, "Future intelligent and secure vehicular network toward 6G: Machine-learning approaches," *Proc. IEEE*, vol. 108, no. 2, pp. 292–307, Feb. 2020.

[8] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, and Y.-J. A. Zhang, "The roadmap to 6G: AI empowered wireless networks," *IEEE Commun. Mag.*, vol. 57, no. 8, pp. 84–90, Aug. 2019.

[9] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, "AI models for green communications towards 6G," *IEEE Commun. Surv. Tut.*, vol. 24, no. 1, pp. 210–247, Jan.–Mar. 2022.

[10] A.-A. A. Boulogeorgos, J. M. Jornet, and A. Alexiou, "Directional terahertz communication systems for 6G: Fact check: A quantitative look," *IEEE Veh. Technol. Mag.*, vol. 16, no. 4, pp. 68–77, Dec. 2021.

[11] I. F. Akyildiz, C. Han, and S. Nie, "Combating the distance problem in the millimeter wave and terahertz frequency bands," *IEEE Commun. Mag.*, vol. 56, no. 6, pp. 102–108, Jun. 2018.

[12] Ö. Özdogan, E. Björnson, and E. G. Larsson, "Intelligent reflecting surfaces: Physics, propagation, and pathloss modeling," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 581–585, May 2020.

[13] X. Yuan, Y.-J. A. Zhang, Y. Shi, W. Yan, and H. Liu, "Reconfigurable-intelligent-surface empowered wireless communications: Challenges and opportunities," *IEEE Wireless Commun.*, vol. 28, no. 2, pp. 136–143, Apr. 2021.

[14] R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, "Reconfigurable holographic surface: Holographic beamforming for metasurface-aided wireless communications," *IEEE Trans. Veh. Technol.*, vol. 70, no. 6, pp. 6255–6259, Jun. 2021.

[15] X. Wan *et al.*, "Multichannel direct transmissions of near-field information," *Light: Sci. Appl.*, vol. 8, no. 1, pp. 1–8, 2019.

[16] M. Di Renzo *et al.*, "Smart radio environments empowered by reconfigurable intelligent surfaces: How it works, state of research, and the road ahead," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 11, pp. 2450–2525, Nov. 2020.

[17] D. Pozar, S. Targonski, and H. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 45, no. 2, pp. 287–296, Feb. 1997.

[18] Z. Luo, J. Long, X. Chen, and D. F. Sievenpiper, "Electrically tunable metasurface absorber based on dissipating behavior of embedded varactors," *Appl. Phys. Lett.*, vol. 109, 2016, Art. no. 071107.

[19] H. Yang *et al.*, "A programmable metasurface with dynamic polarization, scattering and focusing control," *Sci. Rep.*, vol. 6, pp. 1–11, 2016.

[20] V. Arun and H. Balakrishnan, "{RFocus}: Beamforming using thousands of passive antennas," in *Proc. 17th USENIX Symp. Netw. Syst. Des. Implementation*, 2020, pp. 1047–1061.

[21] L. Dai *et al.*, "Reconfigurable intelligent surface-based wireless communications: Antenna design, prototyping, and experimental results," *IEEE Access*, vol. 8, pp. 45913–45923, 2020.

[22] L. W. Wu *et al.*, "Transmission-reflection controls and polarization controls of electromagnetic holograms by a reconfigurable anisotropic digital coding metasurface," *Adv. Opt. Mater.*, vol. 8, no. 22, 2020, Art. no. 2001065.

[23] A. Pitilakis *et al.*, "A multi-functional reconfigurable metasurface: Electromagnetic design accounting for fabrication aspects," *IEEE Trans. Antennas Propag.*, vol. 69, no. 3, pp. 1440–1454, Mar. 2021.

[24] "Docomo conducts world's first successful trial of transparent dynamic metasurface," Accessed: Mar. 30, 2022. [Online]. Available: https://www.nttdocomo.co.jp/english/info/media_center/pr/2020/0117_00.html

[25] R. Karasik, O. Simeone, M. Di Renzo, and S. S. Shitz, "Beyond max-SNR: Joint encoding for reconfigurable intelligent surfaces," in *Proc. IEEE Int. Symp. Inf. Theory*, 2020, pp. 2965–2970.

[26] M. Di Renzo *et al.*, "Reconfigurable intelligent surfaces vs. relaying: Differences, similarities, and performance comparison," *IEEE Open J. Commun. Soc.*, vol. 1, pp. 798–807, 2020.

[27] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, Jan. 2020.

[28] H. Guo, X. Zhou, J. Liu, and Y. Zhang, "Vehicular intelligence in 6G: Networking, communications, and computing," *Veh. Commun.*, vol. 33, 2022, Art. no. 100399.

[29] S. Chen, Y.-C. Liang, S. Sun, S. Kang, W. Cheng, and M. Peng, "Vision, requirements, and technology trend of 6G: How to tackle the challenges of system coverage, capacity, user data-rate and movement speed," *IEEE Wireless Commun.*, vol. 27, no. 2, pp. 218–228, Apr. 2020.

[30] W.-Y. Shieh, W.-H. Lee, S.-L. Tung, B.-S. Jeng, and C.-H. Liu, "Analysis of the optimum configuration of roadside units and onboard units in dedicated short-range communication systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 565–571, Dec. 2006.

[31] J. Lee and C. M. Kim, "A roadside unit placement scheme for vehicular telematics networks," in *Advances in Computer Science and Information Technology*. Cham, Springer, 2010, pp. 196–202.

[32] C. Lochert, B. Scheuermann, C. Wewetzer, A. Luebke, and M. Mauve, "Data aggregation and roadside unit placement for a vanet traffic information system," in *Proc. 5th ACM Int. Workshop Veh. Inter-Netw.*, 2008, pp. 58–65.

[33] M. A. Qureshi and R. M. Noor, "Towards improving vehicular communication in modern vehicular environment," in *Proc. 11th Int. Conf. Front. Inf. Technol.*, 2013, pp. 177–182.

[34] B. Di, H. Zhang, L. Song, Y. Li, Z. Han, and H. V. Poor, "Hybrid beamforming for reconfigurable intelligent surface based multi-user communications: Achievable rates with limited discrete phase shifts," *IEEE J. Sel. Areas Commun.*, vol. 38, no. 8, pp. 1809–1822, Aug. 2020.

[35] J. Nolan, K. Qian, and X. Zhang, "RoS: Passive smart surface for roadside-to-vehicle communication," in *Proc. ACM SIGCOMM Conf.*, 2021, pp. 165–178.

[36] J. Wang, W. Zhang, X. Bao, T. Song, and C. Pan, "Outage analysis for intelligent reflecting surface assisted vehicular communication networks," in *Proc. IEEE Glob. Commun. Conf.*, 2020, pp. 1–6.

[37] Y. Chen, Y. Wang, and L. Jiao, "Robust transmission for reconfigurable intelligent surface aided millimeter wave vehicular communications with statistical CSI," *IEEE Trans. Wireless Commun.*, vol. 21, no. 2, pp. 928–944, Feb. 2022.

[38] K. Heimann, A. Marsch, B. Sliwa, and C. Wietfeld, "Reflecting surfaces for beyond line-of-sight coverage in millimeter wave vehicular networks," in *Proc. IEEE Veh. Netw. Conf.*, 2020, pp. 1–4.

[39] T. Saeed *et al.*, "On the use of programmable metasurfaces in vehicular networks," in *Proc. IEEE 22nd Int. Workshop Signal Process. Adv. Wireless Commun.*, 2021, pp. 521–525.

[40] T. Dhruvakumar and A. Chaturvedi, "Intelligent reflecting surface assisted millimeter wave communication for achievable rate and coverage enhancement," *Veh. Commun.*, vol. 33, 2022, Art. no. 100431.

[41] S. Hu, F. Rusek, and O. Edfors, "Beyond massive MIMO: The potential of positioning with large intelligent surfaces," *IEEE Trans. Signal Process.*, vol. 66, no. 7, pp. 1761–1774, Apr. 2018.

[42] J. He, H. Wymeersch, L. Kong, O. Silvén, and M. Juntti, "Large intelligent surface for positioning in millimeter wave mimo systems," in *Proc. IEEE 91st Veh. Technol. Conf.*, 2020, pp. 1–5.

[43] E. Basar, I. Yildirim, and F. Kilinc, "Indoor and outdoor physical channel modeling and efficient positioning for reconfigurable intelligent surfaces in mmwave bands," *IEEE Trans. Commun.*, vol. 69, no. 12, pp. 8600–8611, Dec. 2021.

[44] E. Björnson, L. Sanguinetti, H. Wymeersch, J. Hoydis, and T. L. Marzetta, “Massive mimo is a reality–what is next?: Five promising research directions for antenna arrays,” *Digit. Signal Process.*, vol. 94, pp. 3–20, 2019.

[45] L. Lei, D. Yuan, C. K. Ho, and S. Sun, “Power and channel allocation for non-orthogonal multiple access in 5G systems: Tractability and computation,” *IEEE Trans. Wireless Commun.*, vol. 15, no. 12, pp. 8580–8594, Dec. 2016.

[46] Y. Chen, Y. Wang, J. Zhang, and M. Di Renzo, “QoS-driven spectrum sharing for reconfigurable intelligent surfaces (RISs) aided vehicular networks,” *IEEE Trans. Wireless Commun.*, vol. 20, no. 9, pp. 5969–5985, Sep. 2021.

[47] Y. Chen, Y. Wang, J. Zhang, and Z. Li, “Resource allocation for intelligent reflecting surface aided vehicular communications,” *IEEE Trans. Veh. Technol.*, vol. 69, no. 10, pp. 12321–12326, Oct. 2020.

[48] A. Al-Hilo, M. Shokry, M. Elhattab, C. Assi, and S. Sharafeddine, “Reconfigurable intelligent surface enabled vehicular communication: Joint user scheduling and passive beamforming,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 2333–2345, Mar. 2022.

[49] H. Zhao, X. Zhang, J. Hu, Z. D. Chen, and Y.-C. Liang, “A hybrid-equivalent surface-edge current model for simulation of V2X communication antennas with arbitrarily shaped contour,” *IEEE Internet Things J.*, vol. 8, no. 10, pp. 8064–8077, May 2021.

[50] Z. Huang, B. Zheng, and R. Zhang, “Transforming fading channel from fast to slow: Irs-assisted high-mobility communication,” in *ICC Proc. IEEE Int. Conf. Commun.*, 2021, pp. 1–6.

[51] Y. Zhu, B. Mao, Y. Kawamoto, and N. Kato, “Intelligent reflecting surface-aided vehicular networks toward 6G: Vision, proposal, and future directions,” *IEEE Veh. Technol. Mag.*, vol. 16, no. 4, pp. 48–56, Dec. 2021.

[52] “ETSI- Multi-access edge computing (MEC),” Accessed: Jan. 21, 2022. [Online]. Available: https://www.etsi.org/technologies/multi-access952edge-computing

[53] Y. Liu, X. Guan, Y. Peng, H. Chen, T. Ohtsuki, and Z. Han, “Blockchain based task offloading for edge computing on low-quality data via distributed learning in the internet of energy,” *IEEE J. Sel. Areas Commun.*, vol. 40, no. 2, pp. 657–676, Feb. 2022.

[54] B. Mao, F. Tang, Y. Kawamoto, and N. Kato, “Optimizing computation offloading in satellite-UAV-served 6G IoT: A deep learning approach,” *IEEE Netw.*, vol. 35, no. 4, pp. 102–108, July/Aug. 2021.

[55] X. Chen, L. Jiao, W. Li, and X. Fu, “Efficient multi-user computation offloading for mobile-edge cloud computing,” *IEEE/ACM Trans. Netw.*, vol. 24, no. 5, pp. 2795–2808, Oct. 2016.

[56] Y. Zhu, B. Mao, and N. Kato, “A dynamic task scheduling strategy for multi-access edge computing in IRS-aided vehicular networks,” *IEEE Trans. Emerg. Topics Comput.*, to be published, doi: 10.1109/TETC.2022.3153494.

[57] E. Schoitsch, C. Schmittner, Z. Ma, and T. Gruber, “The need for safety and cyber-security co-engineering and standardization for highly automated automotive vehicles,” in *Advanced Microsystems for Automotive Applications*, Berlin/Heidelberg, Germany: Springer, 2016, pp. 251–261.

[58] K. Zhang, Y. Mao, S. Leng, Y. He, and Y. Zhang, “Mobile-edge computing for vehicular networks: A promising network paradigm with predictive off-loading,” *IEEE Veh. Technol. Mag.*, vol. 12, no. 2, pp. 36–44, Jun. 2017.

[59] X. Yu, D. Xu, and R. Schober, “Enabling secure wireless communications via intelligent reflecting surfaces,” in *Proc. IEEE Glob. Commun. Conf.*, 2019, pp. 1–6.

[60] A. U. Makarfi, K. M. Rabie, O. Kaiwartya, X. Li, and R. Kharel, “Physical layer security in vehicular networks with reconfigurable intelligent surfaces,” in *Proc. IEEE 91st Veh. Technol. Conf.*, 2020, pp. 1–6.

[61] M. Cui, G. Zhang, and R. Zhang, “Secure wireless communication via intelligent reflecting surface,” *IEEE Wireless Commun. Lett.*, vol. 8, no. 5, pp. 1410–1414, Oct. 2019.

[62] Y. Ai, A. Felipe, L. Kong, M. Cheffena, S. Chatzinotas, and B. Ottersten, “Secure vehicular communications through reconfigurable intelligent surfaces,” *IEEE Trans. Veh. Technol.*, vol. 70, no. 7, pp. 7272–7276, Jul. 2021.

[63] L. Gupta, R. Jain, and G. Vaszkun, “Survey of important issues in uav communication networks,” *IEEE Commun. Surv. Tut.*, vol. 18, no. 2, pp. 1123–1152, Apr.-Jun. 2016.

[64] O. K. Sahingoz, “Networking models in flying ad-hoc networks (FANETs): Concepts and challenges,” *J. Intell. Robotic Syst.*, vol. 74, no. 1, pp. 513–527, 2014.

[65] “Air to ground communications,” Accessed: Jan. 21, 2022. [Online]. Available: https://www.acgsys.com/solutions/air-to-ground-communications/

[66] N. Cheng *et al.*, “Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities,” *IEEE Commun. Mag.*, vol. 56, no. 8, pp. 26–32, Aug. 2018.

[67] H. Li, Y. Zhang, J. Xi, and W. Guo, “3D beam tracking method based on reconfigurable intelligent surface assistant for blocking channel,” in *Proc. 36th Youth Academic Annu. Conf. Chin. Assoc. Automat.*, 2021, pp. 684–689.

[68] A. Mahmoud, S. Muhaidat, P. C. Sofotasios, I. Abualhaol, O. A. Dobre, and H. Yanikomeroglu, “Intelligent reflecting surfaces assisted UAV communications for IoT networks: Performance analysis,” *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 3, pp. 1029–1040, Sep. 2021.

[69] P. Mursia, F. Devoti, V. Sciancalepore, and X. Costa-Pérez, “RISe of flight: RIS-empowered UAV communications for robust and reliable air-to-ground networks,” *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1616–1629, 2021.

[70] X. Pang, M. Sheng, N. Zhao, J. Tang, D. Niyato, and K.-K. Wong, “When UAV meets IRS: Expanding air-ground networks via passive reflection,” *IEEE Wireless Commun.*, vol. 28, no. 5, pp. 164–170, Oct. 2021.

[71] S. Li, B. Duo, M. Di Renzo, M. Tao, and X. Yuan, “Robust secure UAV communications with the aid of reconfigurable intelligent surfaces,” *IEEE Trans. Wireless Commun.*, vol. 20, no. 10, pp. 6402–6417, Oct. 2021.

[72] Y. Cai, Z. Wei, S. Hu, D. W. K. Ng, and J. Yuan, “Resource allocation for power-efficient irs-assisted UAV communications,” in *Proc. IEEE Int. Conf. Commun. Workshops*, 2020, pp. 1–7.

[73] K. Heimann, B. Sliwa, M. Patchou, and C. Wietfeld, “Modeling and simulation of reconfigurable intelligent surfaces for hybrid aerial and ground-based vehicular communications,” in *Proc. 24th Int. ACM Conf. Model., Anal. Simul. Wireless Mobile Syst.*, Assoc. Comput. Mach., New York, NY, USA, 2021, pp. 67–74, doi: 10.1145/3479239.3485700.

[74] A. Ranjha and G. Kaddoum, “URLLC facilitated by mobile UAV relay and RIS: A joint design of passive beamforming, blocklength, and uav positioning,” *IEEE Internet Things J.*, vol. 8, no. 6, pp. 4618–4627, Mar. 2021.

[75] D. Ma, M. Ding, and M. Hassan, “Enhancing cellular communications for UAVs via intelligent reflective surface,” in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2020, pp. 1–6.

[76] Z. Mohamed and S. Aïssa, “Leveraging UAVs with intelligent reflecting surfaces for energy-efficient communications with cell-edge users,” in *Proc. IEEE Int. Conf. Commun. Workshops*, 2020, pp. 1–6.

[77] H. Hashida, Y. Kawamoto, and N. Kato, “Intelligent reflecting surface placement optimization in air-ground communication networks toward 6G,” *IEEE Wireless Commun.*, vol. 27, no. 6, pp. 146–151, Dec. 2020.

[78] B. Zheng, Q. Wu, and R. Zhang, “Intelligent reflecting surface-assisted multiple access with user pairing: NOMA or OMA?,” *IEEE Commun. Lett.*, vol. 24, no. 4, pp. 753–757, Apr. 2020.

[79] J. Zuo, Y. Liu, E. Basar, and O. A. Dobre, “Intelligent reflecting surface enhanced millimeter-wave NOMA systems,” *IEEE Commun. Lett.*, vol. 24, no. 11, pp. 2632–2636, Nov. 2020.

[80] X. Liu, Y. Liu, and Y. Chen, “Machine learning empowered trajectory and passive beamforming design in UAV-RIS wireless networks,” *IEEE J. Sel. Areas Commun.*, vol. 39, no. 7, pp. 2042–2055, Jul. 2021.

[81] S. Jiao, F. Fang, X. Zhou, and H. Zhang, “Joint beamforming and phase shift design in downlink UAV networks with IRS-assisted NOMA,” *J. Commun. Inf. Netw.*, vol. 5, no. 2, pp. 138–149, 2020.

[82] W. Chen, X. Ma, Z. Li, and N. Kuang, “Sum-rate maximization for intelligent reflecting surface based terahertz communication systems,” in *Proc. IEEE/CIC Int. Conf. Commun. Workshops China*, 2019, pp. 153–157.

[83] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, “Sum-rate maximization for intelligent reflecting surface assisted terahertz communications,” *IEEE Trans. Veh. Technol.*, vol. 71, no. 3, pp. 3320–3325, Mar. 2022.

[84] X. Ma *et al.*, “Joint channel estimation and data rate maximization for intelligent reflecting surface assisted terahertz mimo communication systems,” *IEEE Access*, vol. 8, pp. 99565–99581, 2020.

[85] Y. Pan, K. Wang, C. Pan, H. Zhu, and J. Wang, "Uav-assisted and intelligent reflecting surfaces-supported terahertz communications," *IEEE Wireless Commun. Lett.*, vol. 10, no. 6, pp. 1256–1260, 2021.

[86] Y. Tan, J. Wang, J. Liu, and N. Kato, "Blockchain-assisted distributed and lightweight authentication service for industrial unmanned aerial vehicles," *IEEE Internet Things J.*, to be published, doi: 10.1109/JIOT.2022.3142251.

[87] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A tutorial on UAVs for wireless networks: Applications, challenges, and open problems," *IEEE Commun. Surv. Tut.*, vol. 21, no. 3, pp. 2334–2360, Jul.-Sep. 2019.

[88] L. Xie, J. Xu, and R. Zhang, "Throughput maximization for UAV-enabled wireless powered communication networks," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 1690–1703, Apr. 2019.

[89] Z. LI, W. Wang, J. Guo, Y. Zhu, L. Han, and Q. Wu, "Blockchain-empowered dynamic spectrum management for space-air-ground integrated network," *Chin. J. Electron.*, vol. 31, no. 3, pp. 1–11, 2022.

[90] W. Wang, N. Cheng, Y. Liu, H. Zhou, X. Lin, and X. Shen, "Content delivery analysis in cellular networks with aerial caching and mmwave backhaul," *IEEE Trans. Veh. Technol.*, vol. 70, no. 5, pp. 4809–4822, May 2021.

[91] Y.-H. Hsu and R.-H. Gau, "Reinforcement learning-based collision avoidance and optimal trajectory planning in UAV communication networks," *IEEE Trans. Mobile Comput.*, vol. 21, no. 1, pp. 306–320, Jan. 2022.

[92] Y. Zeng, X. Xu, and R. Zhang, "Trajectory design for completion time minimization in UAV-enabled multicasting," *IEEE Trans. Wireless Commun.*, vol. 17, no. 4, pp. 2233–2246, Apr. 2018.

[93] Z. Liu, S. Zhao, Q. Wu, Y. Yang, and X. Guan, "Joint trajectory design and resource allocation for IRS-assisted UAV communications with wireless energy harvesting," *IEEE Commun. Lett.*, vol. 26, no. 2, pp. 404–408, Feb. 2022.

[94] S. Li, B. Duo, X. Yuan, Y.-C. Liang, and M. Di Renzo, "Reconfigurable intelligent surface assisted UAV communication: Joint trajectory design and passive beamforming," *IEEE Wireless Commun. Lett.*, vol. 9, no. 5, pp. 716–720, May 2020.

[95] H. Mei, K. Yang, J. Shen, and Q. Liu, "Joint trajectory-task-cache optimization with phase-shift design of RIS-assisted UAV for MEC," *IEEE Wireless Commun. Lett.*, vol. 10, no. 7, pp. 1586–1590, Jul. 2021.

[96] "Why amazon, ups and even domino's is investing in drone delivery services," Accessed: Jan. 21, 2022. [Online]. Available: https://www.businessinsider.com/drone-delivery-services

[97] M. Mao, N. Cao, R. Li, and R. Shi, "IRS-assisted low altitude passive aerial relaying," *Comput. Commun.*, vol. 175, pp. 150–155, 2021.

[98] S. Hu and F. Rusek, "Spherical large intelligent surfaces," in *Proc. IEEE Int. Conf. Acoust. Speech Signal Process.*, 2020, pp. 8673–8677.

[99] H. Lu, Y. Zeng, S. Jin, and R. Zhang, "Aerial intelligent reflecting surface: Joint placement and passive beamforming design with 3D beam flattening," *IEEE Trans. Wireless Commun.*, vol. 20, no. 7, pp. 4128–4143, Jul. 2021.

[100] M. Al-Jarrah, E. Alsusa, A. Al-Dweik, and D. K. So, "Capacity analysis of IRS-based UAV communications with imperfect phase compensation," *IEEE Wireless Commun. Lett.*, vol. 10, no. 7, pp. 1479–1483, Jul. 2021.

[101] H. Long *et al.*, "Reflections in the sky: Joint trajectory and passive beamforming design for secure UAV networks with reconfigurable intelligent surface," 2020, *arXiv:2005.10559*.

[102] A. S. Abdalla, T. F. Rahman, and V. Marojevic, "UAVs with reconfigurable intelligent surfaces: Applications, challenges, and opportunities," 2020, *arXiv:2012.04775*.

[103] B.-R. Wu and L.-C. Wang, "Learning from UAV experimental results for performance modeling of reconfigurable intelligent surface flying platform," in *Proc. 30th Wireless Opt. Commun. Conf.*, 2021, pp. 245–250.

[104] B. Shang, R. Shafin, and L. Liu, "UAV swarm-enabled aerial reconfigurable intelligent surface (SARIS)," *IEEE Wireless Commun.*, vol. 28, no. 5, pp. 156–163, Oct. 2021.

[105] N. Chang, C.-B. Chae, J. Ha, and J. Kang, "Secrecy rate for MISO rayleigh fading channels with relative distance of eavesdropper," *IEEE Commun. Lett.*, vol. 16, no. 9, pp. 1408–1411, Sep. 2012.

[106] J. Sun, S. Zhang, and K. Chi, "Secrecy performance maximization for underlay CR networks with an energy harvesting jammer," *Sensors*, vol. 21, no. 24, 2021, Art. no. 8198.

[107] W. Wang, H. Tian, and W. Ni, "Secrecy performance analysis of IRS-aided UAV relay system," *IEEE Wireless Commun. Lett.*, vol. 10, no. 12, pp. 2693–2697, Dec. 2021.

[108] R. Sun, W. Wang, L. Chen, G. Wei, and W. Zhang, "Diagnosis of intelligent reflecting surface in millimeter-wave communication systems," *IEEE Trans. Wireless Commun.*, to be published, doi: 10.1109/TWC.2021.3125734.

[109] Y. Jia, C. Ye, and Y. Cui, "Analysis and optimization of an intelligent reflecting surface-assisted system with interference," *IEEE Trans. Wireless Commun.*, vol. 19, no. 12, pp. 8068–8082, Dec. 2020.

[110] X. Hu, C. Masouros, and K.-K. Wong, "Reconfigurable intelligent surface aided mobile edge computing: From optimization-based to location-only learning-based solutions," *IEEE Trans. Commun.*, vol. 69, no. 6, pp. 3709–3725, Jun. 2021.

[111] Z. Wang, L. Liu, and S. Cui, "Channel estimation for intelligent reflecting surface assisted multiuser communications," in *Proc. IEEE Wireless Commun. Netw. Conf.*, 2020, pp. 1–6.

[112] S. Zhang and R. Zhang, "Intelligent reflecting surface aided multiple access: Capacity region and deployment strategy," in *Proc. IEEE 21st Int. Workshop Signal Process. Adv. Wireless Commun.*, 2020, pp. 1–5.

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