

Review of UAV based on Reconfigurable Intelligent Surface and ISAC

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Abstract

This paper discusses the application of Reconfigurable Intelligent Surface (RIS) technology combined with Unmanned Aerial Vehicle (UAV) technology, and discusses their innovative potential in 6G communication networks. Especially in the field of Integrated Sensing and Communication (ISAC) application prospects. RIS is a two-dimensional surface based on electromagnetic metamaterial technology. Through dynamic regulation of electromagnetic units, parameters such as phase and amplitude of incident electromagnetic waves can be flexibly controlled, so as to optimize wireless channel and improve communication performance. Compared with traditional communication systems, RIS has the advantages of low cost, low power consumption and easy deployment, which can significantly improve the stability and coverage of UAS communication links. Through in-depth analysis of the working principle, hardware architecture and advantages of RIS combined with UAV, this paper elaborates its application scenarios in UAV network, including disaster relief, urban management, intelligent transportation and battlefield reconnaissance. With RIS's intelligent beamforming and channel optimization, UAVs can not only provide efficient communication services, but also enable accurate environment awareness and target tracking. In addition, this paper analyzes the key challenges faced by RIS-assisted UAVs in practical engineering applications, such as the complexity of channel estimation, multi-UAV cooperative communication, and adaptability in dynamic environments. By proposing several solutions, including optimizing channel estimation technology and improving beamforming design, this paper provides theoretical basis and technical support for the wide application of RIS and UAV in 6G networks in the future. The research shows that the introduction of RIS technology will greatly improve the communication ability of UAVs in complex environments, and promote the integration of communication and perception in the 6G era.

Keywords

Intelligent Reflector (RIS); Unmanned Aerial Vehicle (UAV); Communication and Perception Integration; 6G; Channel Estimation; Beamforming.

1. Introduction

1.1. Research Background and Significance

With the development and deepening of modern 5G communication, it has gradually failed to meet the increasing demands of modern communication, artificial intelligence, big data, and other technologies. The sixth generation wireless communication system (6G) for the future will expand and deepen based on the three typical scenarios of 5G (enhanced mobile broadband, massive connectivity, and ultra-reliable low latency). And it will use technological innovation to connect the physical world with the digital world, which will lead to a series of new services

with virtual space as the main body of the connection, such as drone clusters, immersive experiences, holographic communication, and digital twins [1]. The emerging applications in smart cities, smart transportation, and smart factories pose unprecedented demands for ultra-low latency, ultra-high reliability, and ultra-high-speed communication in wireless networks [2]. However, due to the exponential growth in the number of wireless devices accessing networks, the communication and sensing systems among these devices often utilize different spectrum resources. This will cause the already insufficient spectrum resources to become even tighter, making the global communications industry's demand for wireless spectrum resources increasingly urgent [3].

Spectrum resources are fundamental to the development of mobile communications. To resolve the conflict between limited bandwidth resources and ubiquitous connectivity, there is an urgent need to explore additional spectrum resources and develop new communication technologies to meet the growing demands for information processing [4]. On one hand, 6G will continue to develop high-quality available spectrum by further exploring higher frequency bands such as millimeter waves, terahertz waves, and visible light while improving the utilization of existing spectrum resources. By comprehensively and efficiently utilizing different frequency band spectrum resources, we can address challenges related to spectrum scarcity and capacity limitations in 6G's Internet of Everything [5]. On the other hand, there is increasing overlap between wireless communication and traditional sensing in terms of hardware architecture, frequency band resources, and data processing. Integrated Sensing and Communication (ISAC), which is based on shared software and hardware resources or information resources while simultaneously achieving sensing and communication functions, has garnered widespread attention from both academia and industry [6]. The 5G primarily focuses on high bandwidth, high speed, and low latency communication needs-and possesses some environmental sensing capabilities, but the application of ISAC technology within 5G remains relatively limited. In contrast, 6G is expected to be a fully integrated network system that merges communication with sensing functionalities; ISAC will be one of its core technologies. Since ISAC can utilize a single set of devices to send and sense signals while achieving both communication and sensing functions within the same frequency band, it enhances system spectrum efficiency, hardware efficiency, and information processing efficiency-effectively alleviating the increasing tension on spectrum resources and current capacity limitations in wireless systems. However, the increasingly complex propagation environment poses significant attenuation risks and security threats to ISAC transmissions, resulting in degraded system performance [7-8]. Therefore, innovative technologies must be developed to meet the sensing requirements and performance metrics of 6G ISAC networks.

In the future, with a vision of "ubiquitous intelligent connectivity," 6G wireless networks will have more complex requirements in terms of both dimensions and breadth of wireless connections. They will need to support device densities of at least 10^7 devices/km² as well as mobility speeds exceeding 1000 km/h. Traditional wireless communication methods rely heavily on ground infrastructure but are constrained by environmental factors that result in incomplete network coverage and poor signal quality-making it difficult to adapt quickly to changing task demands. By employing Unmanned Aerial Vehicles (UAVs) as temporary base stations or relay nodes, we can extend terrestrial IoT into three-dimensional space, facilitating cooperation between low-altitude communication networks and ground networks. Additionally, thanks to their high mobility and rapid deployment capabilities, UAVs can flexibly adapt to complex environments such as disaster areas, oceans, urban settings, or wilderness regions-achieving extensive network coverage [9]. However, UAVs utilizing traditional communication methods face numerous challenges:

1.1.1. Poor Communication Link Stability

UAVs often move at high speeds through the air; traditional communication methods (such as those relying on ground base stations or satellite communications) frequently experience unstable signals when addressing these movements.

1.1.2. Limited Communication Coverage

Traditional communication methods primarily depend on ground base stations or satellites for communication, that creates blind spots for UAVs in remote or complex terrain areas.

1.1.3. High Energy Consumption

Traditional communication methods often require high-power wireless transmitters and receivers on UAVs to ensure adequate communication range and signal strength; however, this design significantly increases energy consumption and reduces flight endurance.

1.1.4. Weight and Size Limitations of Communication Equipment

UAV size restrictions limit payload capacity; traditional communication equipment (like high-gain antennas or large power amplifiers) tends to be bulky or heavy, impacting UAV maneuverability and endurance.

1.1.5. Challenges in Multi-UAV Cooperative Communication

Traditional UAV communication approaches lack efficient coordination mechanisms when multiple UAVs work collaboratively, resulting in low inter-UAV communication efficiency.

1.1.6. Poor Adaptability in Dynamic Environments

During flight operations, UAVs encounter variations in altitude or speed along with dynamic changes in surrounding environments (such as weather conditions or buildings); traditional systems struggle to maintain effective communication links amidst these changes.

RIS (Reconfigurable Intelligent Surface) integrated by passive electromagnetic components can intelligently reconfigure the wireless propagation environment, which greatly improves the problems encountered above, and has gained extensive attention from academia and industry [10].

RIS is an artificial electromagnetic surface structure with programmable electromagnetic properties, developed from metamaterial technology [11]. Abundant electromagnetic units are regularly arranged on its surface, and by applying control signals to each electromagnetic unit, the electromagnetic properties of the electromagnetic units (e.g., capacitive impedance, impedance, and inductive impedance, etc.) can be dynamically adjusted to complete the dynamic regulation of electromagnetic waves in space, and then intelligently adjust the wireless transmission channel and reconfigure the wireless propagation environment [12].

1.2. Current Research Status at Home and Abroad

Currently, both academia and industry have established corresponding organizations and forums, initiating a series of activities to accelerate the commercialization and industrialization of Reconfigurable Intelligent Surface (RIS) technology. In June 2020, the Wireless Technology Group of the IMT-2030 (6G) Promotion Group established the "RIS Task Force" [13]. On September 24, 2021, the first RIS Technology Forum was held in Beijing [14]. On April 7, 2022, the RIS Technology Alliance was founded in Beijing. The establishment of this alliance is expected to effectively promote research on related technologies and advance efforts in standardization and industrialization of RIS technology, thereby collaboratively building an RIS ecosystem [15].

To verify the feasibility of RIS technology, research institutions both domestically and internationally have conducted a series of testing and validation studies on RIS-based communication systems. Domestically, China Mobile collaborated with Southeast University to carry out outdoor testing of RIS. The test results indicated that RIS can enhance average

coverage at the cell edge by approximately 3 to 4 dB, with user equipment (UE) throughput increasing by more than ten times [16]. The ZTE Corporation and China Telecom completed the industry's first outdoor testing validation of RIS for high-frequency 5G communications. In non-line-of-sight blind spots or weak signal areas over 150 meters from a 5G high-frequency (26 GHz) base station (BS), using RIS increased UE's received signal strength by 12.5 dB [17]. Tsinghua University developed an RIS device containing 256 two-bit discrete phase control units, achieving an antenna gain of 21.7 dBi at a frequency of 2.3 GHz and a gain of 19.1 dBi at a frequency of 28.5 GHz [18].

Internationally, Japan's DoCoMo company conducted the world's first outdoor testing on RIS in 2018, demonstrating that using RIS at a frequency of 28 GHz could enhance communication rates by up to 500 Mbit/s [19]. The Massachusetts Institute of Technology (MIT) established a testing platform called RFocus operating in the unlicensed frequency band of 2.4 GHz, which showed that RIS could double channel capacity in indoor scenarios [20]. Researchers at the University of California, San Diego conducted tests on commercial multiple input multiple output (MIMO) Wi-Fi networks, ultimately finding that RIS could extend Wi-Fi coverage from 30 meters to 45 meters while doubling data rates in the reception area [21]. Although RIS has shown significant performance improvements in mobile communication fields, numerous issues and challenges still exist in practical engineering applications. This paper will provide a comprehensive summary and discussion on RIS technology in drone communication networks from various aspects including fundamental principles, major technical advantages, application scenarios, key technologies, and primary challenges.

2. Review

2.1. Fundamental Principles of RIS

Electromagnetic metamaterials are composite materials synthesized artificially, characterized by specific electromagnetic properties arranged in a periodic structure. They possess two fundamental features: they are artificially synthesized, and their electromagnetic properties are determined not by the materials themselves but by the artificial structures within them [22]. Reconfigurable Intelligent Surfaces (RIS) are developed based on the technology of electromagnetic metamaterials; they represent a two-dimensional surface with special electromagnetic properties that are processed or synthesized artificially. The hardware architecture of RIS is illustrated in Figure 1, which depicts a typical RIS hardware configuration consisting of three layers of substrates and an intelligent controller [23]. The outermost layer is a dielectric substrate, on which numerous electromagnetic units are regularly arranged. These units typically consist of metals, dielectrics, and tunable components, with the tunable components potentially being varactor diodes or positive-intrinsic-negative (PIN) diodes (the tunable component shown in the electromagnetic unit in Figure 1 is a PIN diode). By controlling the bias voltage applied to these tunable components, the electromagnetic properties of each unit can be adjusted. Consequently, RIS can dynamically and effectively adjust parameters such as the amplitude and phase of incident signals in real-time based on feedback from communication link information regarding signal propagation through software programming, thereby achieving intelligent control over electromagnetic waves [24-25]. The control signals for the control circuit board are triggered by an intelligent controller connected to it. In practical applications, Field Programmable Gate Arrays (FPGAs) can serve as intelligent controllers for RIS [23].

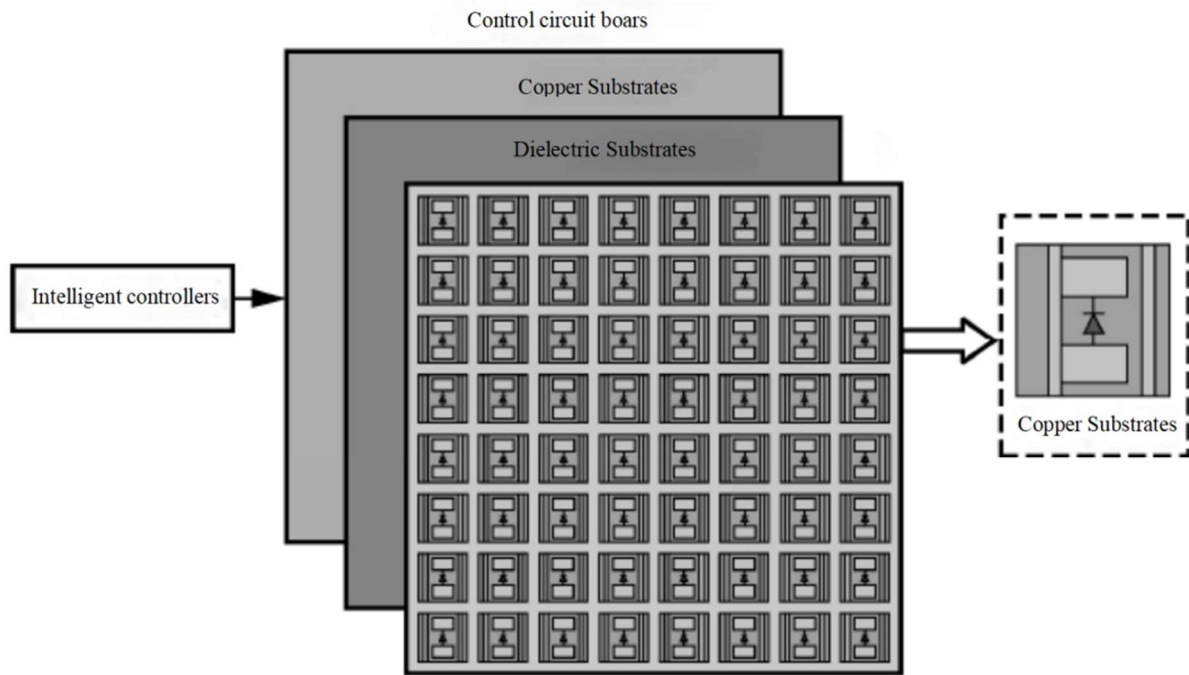


Fig. 1 RIS hardware architecture

2.2. Key Technical Advantages

Compared to traditional UAV communication devices, RIS offers significant advantages in terms of hardware costs and power consumption.

2.2.1. Low Hardware Costs

Traditional phased arrays require devices such as phase shifters and power amplifiers to be connected to each antenna unit [26] to achieve beamforming in the analog domain. In contrast, RIS does not need many phase shifters or power amplifiers; instead, it integrates lower-cost devices like PIN diodes or varactor diodes within each electromagnetic unit. By controlling the bias voltage of these devices, the phase response of each electromagnetic unit can be altered, thereby enabling beamforming in the analog domain. As a result, RIS has relatively lower hardware costs compared to traditional phased arrays and can be deployed in large quantities within low-cost UAV swarms.

2.2.2. Low Power Consumption

The electromagnetic units on RIS primarily consist of passive elements that mainly serve to intelligently adjust the phase of incident signals without ability to power amplify the signal. Moreover, compared to traditional communication devices, RIS does not incorporate high-power-consuming components; thus, it has significant advantages regarding power consumption. Reference [27] describes a prototype design for an RIS operating at a frequency of 5.8 GHz containing 1,100 electromagnetic units, with measured total power consumption at 0.934 W. Detailed power consumption data for this RIS is provided in Table 1, showing that all device units on the RIS exhibit overall low power consumption, ensuring that it can operate for extended periods when powered by small lithium batteries on UAVs.

Table 1. Detailed power consumption data of RIS

Device name	Power consumption /w
Bidirectional Voltage Converter	0.013 8
Level Regulator	0.918
Varactor diodes	0.176

2.2.3. Ease of Deployment

As a two-dimensional structure made from electromagnetic metamaterials, RIS panels have thicknesses much smaller than the wavelengths of radio waves; they are lightweight and do not integrate numerous complex hardware components. Consequently, their deployment is more flexible compared to traditional communication devices; they can be installed on UAVs, vehicles, indoor walls, etc. In addition, the number of electromagnetic units included in a RIS can be adjusted to meet actual communication needs, greatly increasing operational flexibility.

2.2.4. No Additional Latency or Thermal Noise Introduced

Traditional communication devices introduce additional processing latency and thermal noise when receiving, processing, and transmitting signals. In contrast, RIS relies solely on the physical characteristics of passive electromagnetic units to achieve phase adjustments for incident signals without any signal processing steps involved; therefore, it does not introduce extra signal processing latency or thermal noise.

3. UAV Applications in Integrated Sensing and Communication based on RIS

Thanks to their low cost, high mobility, and flexible deployment, RIS-assisted UAV terrestrial-aerial integrated networks have become an active research hotspot in the field of mobile communications. They play a crucial role in disaster relief, emergency support, and multi-dimensional network expansion. In radar sensing services, multipath propagation in non-line-of-sight links is often regarded as harmful interference or clutter, limiting the extraction of useful information solely from line-of-sight links. Moreover, target echo signals that are far from base stations or obstructed by obstacles suffer severe attenuation, leading to degraded sensing performance. UAVs that hover in the air can serve as base stations or relays to establish stable and reliable LOS links for ground nodes, effectively covering blind spots and providing ground users with high-speed and ubiquitous sensing and communication services [28]. Furthermore, compared to communication systems based on fixed infrastructure, UAVs can leverage their mobility to select optimal hovering positions or flight paths, overcoming environmental factors such as terrain and ground facilities to enhance wireless links and reduce interference. Therefore, by sharing the costs of communication and sensing infrastructure, UAV-integrated sensing and communication can lower system deployment costs while enhancing the intelligence and autonomy of UAVs. This enables them to better adapt to complex and dynamic wireless environments and task requirements [29].

Integrated sensing and communication UAV networks not only achieve high data rate transmission but also unlock various sensing functionalities such as target localization, ranging, tracking, imaging, and environmental reconstruction [30]. The 6G multi-dimensional expanded ISAC network based on UAVs and IRS will meet societal demands grounded in 5G-Advanced air interfaces while realizing more efficient and intelligent sensing and communication capabilities. By continuously optimizing aspects such as integrated waveform design, hardware platform construction, and signal processing technologies, UAVs supported by IRS-assisted ISAC networks are expected to overcome the limitations of current 5G systems as well as environmental constraints. This will enable an expansion from terrestrial networks to aerial networks that can interconnect with satellite-based or maritime networks—fulfilling the requirements for integrated coverage across air, land, sea, and space within 6G networks. Additionally, it will support a range of potential new integrated sensing and communication application scenarios including synchronized imaging and environmental reconstruction, high-precision localization and tracking, enhanced human perception, as well as action and expression recognition [31], as illustrated in Table 2.

Table 2. Application scenarios of passive integrated network based on multi-dimensional extension of UAV and IRS

Scene/application classification	Synchronised imaging and environmental reconstruction	High precision positioning and tracking	Enhanced human senses	Motion and expression recognition
Intelligent transport	3d road imaging	Driverless and assisted driving	Rain and fog road condition monitoring	Safe driving
Environmental monitoring	Uav cluster management	Hydraulic and hydrological monitoring	Pollution and air quality detection	Disability protection services
Public service	Public safety	Disaster emergency management and evacuation	Transport safety	Contactless safety detection
City management	Urban environmental surveillance	Urban civilisation monitoring	Building safety detection	Full-time surveillance
Extreme scene	Battlefield support	Real-time intelligence acquisition	Precision strike support	Hostile target surveillance and detection

4. Technical Challenges of ISAC UAVs based on Reconfigurable Intelligent Surface

With the rapid development of sixth-generation mobile communication technology (6G), the integration of Reconfigurable Intelligent Surfaces (RIS) with Unmanned Aerial Vehicles (UAVs) is evolving alongside the advancement of Integrated Sensing and Communication (ISAC) systems. One of the core characteristics of 6G networks is the ability to achieve a deep fusion of communication and sensing functions in a smarter and more flexible manner, providing more efficient solutions for future smart cities, disaster rescue operations, battlefield reconnaissance, and other fields. As a two-dimensional surface structure with programmable electromagnetic properties, RIS can significantly enhance the stability of UAV communication links and improve sensing accuracy by dynamically controlling the propagation of electromagnetic waves. However, the integration of RIS and UAVs faces a series of technical challenges in practical applications. This section will delve into these challenges and propose corresponding discussions.

4.1. Collaborative Sensing in UAV Swarms

In response to increasingly complex application environments and diverse task requirements, the use of UAVs is evolving towards larger-scale swarming capabilities. UAV swarms exhibit enhanced collaboration, intelligence, and autonomy, allowing for greater continuity and completion of tasks even when individual UAVs fail or are damaged, all while operating at lower costs and higher efficiency. Achieving multi-UAV collaborative ISAC assisted by RIS can further exploit the maneuverability advantages of UAVs, significantly expanding their operational scope and application domains. Collaborative sensing among UAV swarms enables the fusion of multiple UAVs' sensing capabilities and sensor data, facilitating extensive area coverage and monitoring while providing more comprehensive and accurate environmental perception and communication services. However, in practical applications, the collaborative operation between RIS and UAV swarms encounters numerous technical challenges. First, RIS must efficiently share data with the UAV swarm to accurately understand the real-time positions, velocities, and task requirements of each drone within the swarm. As the size of the drone swarm increases, this demand for data sharing becomes more complex and urgent. Second,

since UAV swarms typically operate in dynamically changing wireless environments, RIS needs to promptly adjust its signal reflection patterns to adapt to these complex environmental changes. For example, when a UAV swarm is flying in an urban environment, buildings and other obstacles can affect signal propagation paths; thus, RIS must quickly respond by reconfiguring signal reflections to ensure smooth communication and sensing operations.

4.2. Network Architecture and Networking Design

In high-speed mobile environments, UAV networks often exhibit dynamic, sparse, and intermittent connection topologies. Traditional network architectures struggle to adapt to network topology changes that arise during high-speed flights of drones, especially under complex conditions aimed at multi-UAV collaborative communication, where the stability and reliability of network connection face severe challenges. To enable effective collaboration between UAVs and RIS, it is essential to design a flexible network architecture capable of dynamically adjusting network configurations to ensure continuous communication links.

The introduction of RIS can effectively alleviate some of the problems caused by unstable network connections. By intelligently modulating electromagnetic waves, RIS can dynamically generate optimal reflected signals in the path of UAV flights, improving signal strength and coverage. However, due to the high-speed mobility of UAVs, RIS signal modulation must have a fast response capability. Under extreme conditions, such as bad weather or mountainous areas and other scenes with complex terrain, it is even more difficult for RIS and UAV to work together, and how to keep the network running efficiently in such dynamic environments has become an urgent problem to solve.

4.3. Physical Layer Security

By sharing communication and radar frequencies, the multi-dimensional Integrated Sensing and Communication (ISAC) network based on UAVs and Intelligent Reflecting Surfaces (IRS) can flexibly achieve perception functions such as positioning, ranging, and tracking while providing traditional communication services, effectively supporting various emerging 6G applications. However, the inherent openness and broadcast nature of wireless channels exposes the Line-of-Sight (LoS) links provided by UAVs to malicious attacks such as active interference and passive eavesdropping. When active interference is present, legitimate perception and reception within the system can be degraded by the interfering signals. On the other hand, eavesdroppers can estimate the channel state information between legitimate transmitters and receivers, intercepting confidential user information. Furthermore, compared to traditional communication systems, the high integration of sensing and communication capabilities in ISAC increases the risk of sensitive information leakage. If adversarial attributes are present in the target, this could even lead to information security incidents. Therefore, physical layer security has become a key challenge in the design of multidimensional integrated sensing and communication networks based on UAVs and IRS.

4.4. Channel Estimation

As a high-speed mobile wireless communication platform, UAVs experience rapid changes in position and trajectory that lead to swift variations in the wireless channels of ISAC networks within a short time frames, complicating channel estimation. In addition, IRS typically consists of passive elements that cannot perform baseband signal processing functions; and thus cannot obtain perfect channel state information. At the same time, to increase the signal strength, it is necessary to accurately estimate the phase setting on the reflecting surface to direct and focus the reflected signal. However, errors in phase estimation can lead to signal attenuation, thus degrading the communication performance. In addition, obstacles in the environment and multipath propagation effects introduce uncertainties that make channel estimation more challenging. To improve channel estimation accuracy, current research has proposed deep

learning-based methods that predict future channel variations by learning from historical channel data and environmental features. However, these methods require substantial training data and computational resources, and their generalization capabilities in high-dynamic environments still need further validation. Future research directions should focus on developing low-overhead and low-pilot channel estimation methods to reduce computational complexity while enhancing the system's real-time responsiveness.

4.5. Beamforming Design

Beamforming technology utilizes the correlation between closely spaced antenna array elements to create interference among different array beams, concentrating energy in specific directions to form beams for wide-area coverage and interference suppression. Optimizing both active and passive beamforming in UAV- and IRS-assisted multidimensional ISAC networks can enhance signal strength while improving communication rates and sensing accuracy. Currently, beamforming technology is widely applied in existing standard communications. However, its application in conjunction with RIS and UAVs presents several challenges. First, beamforming requires adjusting the phase distribution of antenna arrays based on real-time UAV positions and trajectories to ensure accurate signal transmission to target areas. Second, in scenarios involving multiple target sensing, beamforming technology must enable multidirectional beam scanning to simultaneously perceive status information from multiple targets. Additionally, beamforming needs to balance different requirements for communication and sensing; in some scenarios, communication may require focused directional beams while sensing might necessitate broad beam scanning. Striking a balance between these two aspects is a significant issue in beamforming design.

4.6. Development of Terahertz Technology Hardware and Beamforming Design

Terahertz (THz) technology offers advantages such as large bandwidth, ultra-dense connectivity, and privacy protection, enabling Tbit/s-level ultra-high-speed data transmission and millimeter-level high-resolution sensing. Leveraging the wireless reconfiguration capabilities of RIS and the mobility of UAVs can provide significant development opportunities for THz wireless network applications. However, compared to other frequency bands, the technology and equipment in the field of THz communication are relatively immature, failing to meet the requirements for analog-to-digital conversion and high-speed baseband processing of ultra-wideband THz signals. In UAV- and IRS-assisted aerial-terrestrial THz wireless networks, traditional channel modeling methods struggle to balance complexity and accuracy. Furthermore, beamforming and adaptive modulation for THz signals face challenges such as complex environmental changes, path loss, multipath interference, and frequency-selective fading. Therefore, there is an urgent need to increase research investment in areas such as high-frequency THz transceiver devices, channel modeling methods, and ultra-wideband baseband signal processing algorithms. This will help fill the technological gaps in device design, network protocols, and hardware validation platforms for integrated sensing and communication in the THz domain, promoting the fusion development and innovative applications of THz integrated sensing and communication networks across multiple layers and broad fields.

5. Summary

This paper summarizes the important role of Reconfigurable Intelligent Surface (RIS) technology in 6G communication systems, particularly its application in ISAC when combined with UAVs. The RIS effectively addresses issues such as signal attenuation, limited communication coverage, and high energy consumption that are prevalent in traditional UAV communication systems due to its advantages of low cost, low power consumption, and flexible deployment. In practical applications, RIS technology not only significantly enhances the

stability and signal quality of UAV communication links but also improves communication coverage and data transmission efficiency through techniques such as beamforming. However, the integration of RIS with UAV still faces numerous challenges in real-world applications, including channel estimation difficulties in highly dynamic environments, physical layer security issues, and communication coordination mechanisms during multi-UAV collaborative operations. This paper analyzes these technical challenges and proposes innovative solutions and optimization design concepts, such as the introduction of low-pilot channel estimation techniques and the optimization of beamforming designs, which aim to promote the further development and application of RIS and UAV technologies in future 6G networks.

Looking ahead, RIS technology is expected to bring revolutionary changes to 6G communication systems, particularly in the realm of UAV communications. The widespread applicability and flexibility of integrated sensing and communication applications will provide efficient support for future smart cities, intelligent transportation systems, disaster relief efforts, and other multi-dimensional application scenarios. Future research should continue to explore optimizations in channel estimation techniques, collaborative communication mechanisms and hardware innovations to provide a more robust technological foundation for wireless communication systems in the 6G era.

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