A review of Key Technologies for UAV-Assisted Intelligent Reflective Surface (RIS) Communication in Low-Altitude Airspace

Haozhe Han
School of Communication Engineering, Xidian University, Xi'an, Shaanxi, China

Abstract: This paper reviews the key technologies for unmanned aerial vehicle (UAV)-assisted smart reflective surface (RIS) communications in 6G low-altitude airspace. By combining the flexibility of UAVs with the low-power wireless environment reconfiguration capabilities of RIS, this system aims to address the challenges of high traffic volume, low energy consumption, and complex electromagnetic environments. The article systematically reviews system architecture, channel modeling, and joint optimization of trajectory and phase shift. Research trends are shifting from static optimization of a single UAV to multi-UAV collaboration and AI-driven real-time predictive control. Analysis shows that integrated systems can achieve up to 87% throughput improvements and enhanced physical layer security. Finally, the article explores core challenges such as cascaded channel estimation and robustness, and outlines future directions such as AI-powered optimization, terahertz applications, and integrated air, land, and sea networks.

Keywords: Intelligent Reflecting Surface (RIS); Unmanned Aerial Vehicle (UAV); Low-altitude Airspace Communication; Collaborative optimization; Energy efficiency

1. Introduction

With the widespread application of emerging fields such as logistics, urban transportation, emergency rescue and Internet of Things (IoT) data collection in low-altitude airspace, there is a huge demand for reliable and efficient communications[1][2]. However, traditional ground communication networks face many limitations. High-frequency band communications are easily blocked by buildings, resulting in the dominance of non-line-of-sight (NLoS) links, high signal penetration loss, and greatly reduced coverage and reliability. Although ultra-large-scale multiple-input multiple-output (MIMO) systems can increase capacity, their high hardware cost, complex signal processing and huge energy consumption make their deployment challenging.

Unmanned aerial vehicles (UAVs) can be used as mobile aerial base stations due to their high maneuverability, autonomously establishing line-of-sight (LoS) links with ground users, effectively avoiding signal obstruction caused by ground obstacles. However, UAVs are battery-powered, and their limited endurance and huge mobile energy consumption are inherent drawbacks. Reconfigurable intelligent metasurfaces (RIS), as an emerging technology, provide a new approach to solving the above problems. RIS consists of a large number of independently controllable passive electromagnetic units, which achieve directional beamforming and wireless propagation environment reconstruction by intelligently adjusting phase and amplitude[3]. RIS does not require an additional radio frequency (RF) link, and therefore has the advantages of low energy consumption and low cost.

The combination of drones and RIS aims to leverage their complementary strengths to create a new, efficient, and flexible communications system. Drones leverage their high maneuverability to deploy the RIS in optimal locations, while the RIS provides signal enhancement to the drone through passive beamforming, reducing the required transmit power and thus extending flight time. Research in this area is evolving from single-drone-RIS systems to multi-drone-RIS collaborative networks to address large-scale, multi-user, and wide-area coverage scenarios.

2. UAV-RIS System Basics

2.1 System Architecture: Typical Model Diagram and Analysis

UAV-assisted RIS communication can be divided into three typical architectures.

2.1.1 Ground building RIS assisted drone communication

As shown in Figure 1, the RIS is deployed in fixed locations, such as building walls. Drones typically serve as mobile base stations or aerial relays, while the RIS acts as a passive reflector, enhancing the communication link between the drone and ground nodes, particularly when the ground nodes are located in non-line-of-sight (NLoS) areas from the drone. This architecture offers the advantage of eliminating the need for the drone to carry a RIS payload, conserving battery life. However, its limitation is that the RIS's relatively fixed location prevents it from dynamically adapting to the drone 's movements.

Figure 1. Ground Building RIS-Assisted UAV Communication Architecture Model

2.1.2 Drones equipped with RIS as aerial relays

This is the most widely studied architecture. In this model, the drone itself is equipped with a RIS, acting as a flexible aerial relay node. When the distance between the ground base station and the user is severely blocked by obstacles (such as high-rise buildings), the drone can leverage its high mobility to autonomously fly to the optimal hovering position. Using its onboard RIS, it reflects the base station signal, establishing a cascade channel that bypasses the obstacle and provides auxiliary communication for the ground user. The outstanding advantages of this architecture lie in its extremely high deployment flexibility and dynamic adaptability. It can achieve full-angle reflection communication and dynamically adjust its optimal position according to complex radio environments. However, its limitations are also obvious. The drone's payload capacity and limited battery life are the main bottlenecks. In addition, optimizing the drone's position and RIS phase shift matrix in real time in highly dynamic environments is a huge challenge.

As shown in Figure 2, the system model includes a single-antenna base station, a UAV equipped with a RIS, and a single-antenna ground user. Due to the long distance between the base station and the ground user and the presence of significant obstacles, the communication quality of the direct link between the base station and the ground user is poor. Therefore, the ground user's reception of the base station's transmitted signal via the direct link is negligible. To ensure stable communication between the base station and the ground user, the UAV carries a RIS equipped with N passive reflectors. This reflects the signal transmitted from the base station to the ground user, effectively improving the system's transmission rate.

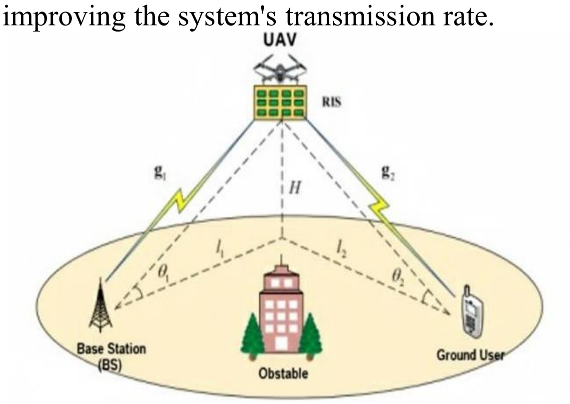

Figure 2. UAV Equipped with RIS as an Aerial Relay Architecture Model [4]

2.1.3 Multi-UAV-RIS collaborative network

The larger transmission distances and the larger number of users on the ground, the efficiency and stability of RIS-assisted communication on a single drone remain relatively low. Therefore, a new architecture, the "multi-drone-RIS collaborative network", is needed.

This architecture represents the future evolution of drone-RIS communications. It consists of multiple drones equipped with RIS, forming a dynamic aerial network. Signals can be transmitted from a base station, reflected by the first drone, and then relayed by a second drone, ultimately reaching the target user on the ground. This multi-hop collaborative network achieves wider coverage and greater robustness than single-drone systems, especially in scenarios where the signal must traverse multiple obstacles or reach a large number of users. A typical application scenario is communications in a large stadium, where signals from an external base station can be relayed by two drones, spanning the stadium's exterior structure, amplifying the signal and reflecting it to the numerous users within. This architectural evolution is essentially a paradigm shift from centralized control to distributed collaboration. In multi-drone networks, task allocation, joint path planning, and beamforming will be key research issues in realizing their potential. This collaboration not only brings performance gains but also introduces new network management and control complexities, as shown in Figure 3.

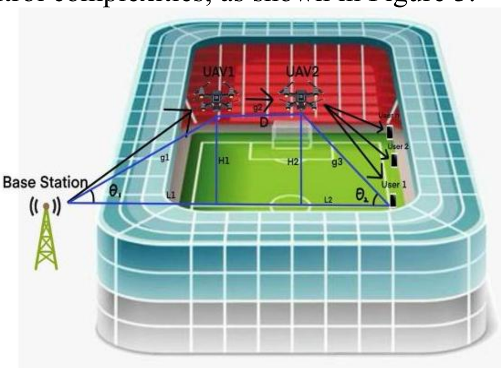

Figure 3. Multi-UAV-RIS Collaborative Network Architecture Model

2.2. Channel Modeling: A2G and RIS Cascade Channel Characteristics

Accurate channel modeling is the basis for designing and optimizing UAV-RIS communication systems, especially focusing on the characteristics of the air-to-ground (A2G) channel and the cascaded channel after the introduction of RIS.

2.2.1 Air-to-Ground (A2G) channel characteristics

Air-to-ground (A2G) communication channels typically have a strong line-of-sight (LoS) component, resulting in better channel conditions than traditional terrestrial fading channels. Therefore, the Rician fading model is often used in research to describe the A2G channel. This model consists of a dominant LoS component and multiple random multipath (NLoS) components. The channel characteristics κ are quantified by the Rician factor (K-factor), which represents the ratio of the LoS component power to the NLoS component power. The altitude of the drone is a key parameter affecting the characteristics of the A2G channel. Research has shown that the Rician factor varies with the drone's elevation angle relative to the ground node θ, and the relationship can be approximately expressed as:

$$\kappa=\exp\left(-\frac{a}{b}+\frac{b\theta}{a}\right) \tag{1}$$

where a and b are environmental parameters. This dependency makes optimizing the UAV's altitude an important means of improving communication performance. Furthermore, in high-speed mobile scenarios (such as high-speed rail), the channel is also subject to severe Doppler shift and rapid fading, which can significantly degrade signal quality and system performance.

2.2.2 Cascade channel characteristics after the introduction of RIS

The unique feature of RIS-assisted communication lies in the cascaded channel it constructs. When obstacles between the base station and the user render the direct link unavailable, RIS uses reflected signals to form a cascaded channel consisting of two links: the "transmitter-RIS" link and the "RIS-receiver" link. The channel model can be expressed as:

$$H_{cascade}=H_{RIS-Receiver}\cdot\Theta\cdot H_{RIS-Transmitter} \tag{2}$$

where $\Theta=\mathrm{diag}\{e^{j\phi_1},e^{j\phi_2},\ldots,e^{j\phi_N}\}$ is the reflection phase shift matrix of the RIS. However, RIS links have an inherent limitation known as the "double fading" effect. Because the cascaded channel consists of two independent wireless links connected in series, its path loss is the product of the path losses of the two links, resulting in a double attenuation of the signal strength relative to the direct link. Therefore, when the direct link is unobstructed, the gain from deploying a RIS may not be significant. The true advantage of RIS lies in scenarios where the direct link is severely blocked or completely unavailable. In these scenarios, RIS can create a new communication path, and its gain is fully realized. The complexity of cascaded channel modeling also poses challenges. Because RIS is a passive device and lacks a radio frequency (RF) chain, it cannot independently process and measure signals. This means that RIS cannot estimate the channel state information (CSI) of the "transmitter-RIS" and "RIS-receiver" channels separately, but can only estimate the entire end-to-end cascaded channel. When the number of reflection units (N) in the RIS is very large, this leads to significant pilot overhead and computational complexity in channel estimation, creating a major gap between theoretical research and practical applications. Therefore, how to design an efficient and low-overhead cascade channel estimation scheme is a key direction for future research.

3. Current Status of Key Technology Research

3.1 Trajectory and Deployment Optimization

Joint optimization of drone trajectories and RIS deployment is the primary step in improving system performance. Its core goal is to maximize system spectrum efficiency, energy efficiency, or coverage by optimizing the drone's spatial position and RIS deployment strategy, while meeting communication quality and energy constraints.

In a single UAV system In the field of RIS, the optimization problem usually involves the joint design of the UAV's three-dimensional coordinates and the RIS phase shift matrix. This problem is extremely challenging due to its variable coupling and non-convex constraints. The mainstream solution includes the alternating optimization (AO) framework, which decomposes the original problem into two sub-problems: UAV trajectory optimization and RIS phase shift optimization, and solves them iteratively [5] . In addition, heuristic algorithms such as particle swarm optimization (PSO) and deep reinforcement learning (DRL) are also widely used to deal with high-complexity problems. For example, a study dynamically adjusted the UAV's altitude by improving the PSO algorithm to maximize the line-of-sight (LoS) probability of the air-to-ground (A2G) link.

For the more realistic multi-UAV cooperative network, the complexity of the optimization problem increases significantly, and it is necessary to comprehensively consider the interference coordination, task allocation and resource management among multiple UAVs. Researchers have proposed a hierarchical optimization strategy: the outer layer uses algorithms such as PSO to optimize the overall deployment position of the UAV group, while the inner layer optimizes the phase shift matrix of each RIS based on techniques such as semidefinite relaxation (SDR). In the STAR-RIS-assisted non-orthogonal multiple access (NOMA) system, some studies have optimized the two-dimensional horizontal position of UAVs by using a linear grid search algorithm to maximize the weighted sum secrecy rate (WSSR). It is worth noting that in high-mobility scenarios (such as high-speed rail communications), traditional static optimization is difficult to cope with the rapid changes in the channel. Therefore, a predictive control method based on kinematic observer and predictor (OPS/OPA) was proposed to achieve forward-looking optimization by predicting the user's future position and adjusting the RIS configuration in advance to compensate for system delays[6].

3.2. Phase Shift Design and Smart Beamforming

The phase shift design of RIS directly determines the effectiveness of its intelligent beamforming. The goal is to achieve coherent superposition of reflected signals at the target receiving end by precisely controlling the phase of each reflector, thereby maximizing the received signal-to-noise ratio (SNR).

3.2.1 Optimization based on channel state information (CSI)

Under ideal conditions where the CSI is known or can be accurately estimated, phase shift optimization is usually solved jointly with problems such as drone trajectory and transmit beamforming. Due to the non-convexity caused by the unit mode constraint, semidefinite relaxation (SDR) is an effective tool for dealing with the phase shift subproblem. SDR relaxes the problem into a convex semidefinite programming (SDP) problem, and after solving it, it recovers the feasible discrete phase shift solution through methods such as Gaussian randomization. Studies have shown that in the RIS-assisted high-speed rail MISO system, by jointly optimizing the RIS phase shift and transmit beamforming, the influence of Doppler frequency shift can be eliminated, and the average channel gain can be increased by about 15 dB, while achieving zero outage probability[7].

3.2.2 Deep learning-based solutions

In actual high-dynamic scenarios, accurately acquiring CSI is costly and difficult. Deep learning, especially deep reinforcement learning (DRL), provides a new approach to solving this problem. For example, the dual-deep deterministic policy gradient (TD3) framework can be used to learn the strategies for drone trajectory and RIS beamforming respectively, and balance spectrum efficiency and energy efficiency through a reward function. Simulations show that such methods can achieve at least a 12% improvement in spectrum efficiency and a 24% improvement in energy efficiency. In addition, the DRL-based solution can achieve intelligent beam tracking under conditions without or with partial CSI, enabling the system to quickly adapt in dynamic environments [5].

3.2.3 Robust design under non-ideal factors

Non-ideal factors in practical systems, such as phase error, can significantly impact system performance. UAV platform jitter and airflow disturbances can cause the RIS phase shift to deviate from the theoretically optimal value. Research has shown that such errors can be modeled as a von Mises distribution, where a larger concentration parameter, κ, reduces the phase error. Phase error degrades beamforming gain, thereby reducing communication rates and physical layer security. Therefore, robustness to phase error must be considered when designing beamforming algorithms, for example, through worst-case optimization or stochastic programming to ensure a lower bound on system performance under non-ideal conditions.

3.3 Resource Allocation

Resource allocation in the UAV-RIS communication system goes beyond the traditional scope of power and spectrum, and extends to the allocation of RIS reflection units, mode selection (such as the reflection/transmission mode switching of STAR-RIS), and scheduling between different users.

The research focuses on the joint optimization of multi-dimensional resources. For example, in a multi-RIS system, by collaboratively adjusting the switching states and phase shifts of multiple RIS, multi-path signals can be coherently superimposed at the receiving end, thereby improving channel capacity. For STAR-RIS, resource allocation also includes optimizing its energy splitting ratio (ES) or mode switching (MS) to balance the communication needs of users in the reflection area and the transmission area. In a hybrid RIS (some units are active) system, resource allocation is more complex, and it is necessary to jointly optimize the amplification gain of the active unit and the phase shift of the passive unit to maximize the perceived signal-to-noise ratio (SNR) or system confidentiality rate while meeting the constraints of secure communication and power budget. A study proposed a joint optimization algorithm based on generalized fractional programming (GFP) and penalized dual decomposition (PDD) for the hybrid RIS-assisted ISAC system, which achieved a balanced improvement in communication and perception performance under non-ideal channel state information (CSI) [8].

3.4 Performance Analysis

Through the optimization of the above key technologies, the UAV-RIS system has demonstrated significant advantages in multiple performance indicators.

3.4.1 Speed and energy efficiency

By jointly optimizing drone trajectories and RIS phase shifts, up to 87% throughput improvement can be achieved in non-line-of-sight (NLoS) scenarios. Compared to the basic method, the DRL-based joint optimization scheme can achieve at least 12% improvement in spectrum efficiency and 24% improvement in energy efficiency. In industrial IoT scenarios, energy efficiency optimization can achieve a 38% reduction in energy consumption [5].

3.4.2 Security

Through precise beam steering, RIS can enhance legitimate user signals while suppressing signals from eavesdroppers. For example, through joint optimization, the eavesdropping channel capacity can be reduced to below 0.1 bps/Hz. In a STAR-RIS-assisted NOMA IoT network, even accounting for phase errors caused by drone jitter, optimized drone deployment can still effectively guarantee the network's Weighted Sum Secrecy Rate (WSSR).

3.4.3 Reliability and robustness

The introduction of RIS has greatly improved the reliability of the system in high-mobility scenarios. In high-speed rail communications, the joint optimization of RIS phase shift and transmit beamforming can effectively compensate for Doppler frequency shift, eliminate the interruption probability existing in traditional solutions, and increase the channel gain by an average of 15 dB [7] . This shows that RIS technology is an effective means to address the challenge of rapid signal fading in high-speed mobile environments.

4. Application Scenarios and Challenges

4.1 Application Scenario

Due to its unique advantages, UAV-assisted RIS communication technology has shown broad application prospects in many fields.

4.1.1 Large stadiums and dense user areas

In extremely densely populated scenarios like sporting events and concerts, ground base stations are prone to overload. A multi-drone-RIS collaborative network can serve as a dynamic supplementary infrastructure, efficiently bringing external signals into the venue via aerial reflection links, addressing peak capacity and interference management challenges.

4.1.2 Emergency communications and wide-area coverage

During natural disasters such as earthquakes and floods, ground-based communication infrastructure may be damaged. Drone-RIS systems can be rapidly deployed to establish temporary communication networks, providing wide-area coverage and emergency communication services to disaster-stricken areas. They are a key component of an integrated air-ground-space network. The EU's TERRAMETA project has demonstrated the application of drone-RIS swarms in emergency communications, achieving a temporary communication network with a coverage radius of 1.5 km.

4.1.3 Internet of Things (IoT) data collection

In IoT networks in smart cities or remote areas, RIS can enhance the communication link between IoT devices and drone-based mobile data aggregation points. This is particularly useful in non-LoS scenarios where IoT devices are located in basements or obscured by buildings, enabling efficient and energy-efficient data collection. Studies have shown that RIS-assisted drone-based IoT data collection is 50% more efficient than traditional systems[9].

4.1.4 High mobility communication guarantee

For high-speed mobile scenarios such as high-speed rail and autonomous driving, the drone-RIS system can dynamically track mobile terminals and compensate for the Doppler effect through real-time beamforming, providing users with stable, high-speed continuous connections, significantly improving travel experience and operational efficiency.

4.1.5 Integrated Sensing and Communications (ISAC)

Future drone-RIS nodes will function not only as communication relays but also as perception platforms. For example, in a hybrid RIS-assisted ISAC system, the RIS can not only enhance the communication link but also use the same signal waveform to perceive the environment or detect potential eavesdroppers, achieving an integrated design of communication and perception functions, improving spectrum efficiency and security.

4.1.6 Border surveillance and high-altitude platforms

UAV-RIS can be used for specialized missions such as wide-area border patrols and ocean monitoring. By collaborating with high-altitude platforms (HAPs) or low-orbit satellites, they can build a seamless, global coverage network that complements both high and low altitudes and integrates air, space, land, and sea. This is key to realizing the vision of 6G ubiquitous connectivity.

4.2 Core Challenges

Despite its huge potential, UAV-RIS communication still faces a series of core challenges that cannot be ignored in its process of practical application.

4.2.1 Channel acquisition: the overhead and challenges of cascaded channel estimation

This is the primary challenge facing the drone-RIS system. As a passive device, the RIS lacks a radio frequency (RF) chain and cannot independently sense and measure the channel. This means that the RIS cannot estimate the CSI of the "transmitter-RIS" and "RIS-receiver" channels separately, but can only estimate the entire end-to-end cascaded channel. When the number of reflective elements (N) in the RIS is large, the number of pilot signals required for channel estimation also increases, resulting in huge channel estimation overhead and latency. Therefore, designing an efficient and low-overhead cascaded channel estimation scheme is a key direction for future research. Future research directions include: leveraging the sparsity and spatiotemporal correlation of the channel, using technologies such as compressed sensing to reduce pilot overhead; or adopting a hybrid RIS architecture with a small number of active elements to assist in channel estimation.

4.2.2 Real-time and robustness: high complexity and non-ideal conditions

The high-speed movement of drones causes rapid changes in channel states, posing severe challenges to the real-time and robustness of the system. The joint optimization problem of drone trajectories and RIS phase shifts is usually highly non-convex and requires complex iterative algorithms (such as SDR) to solve, which results in long computation times. At the same time, positioning systems such as the Global Navigation Satellite System (GNSS) usually have a low update rate (1-20 Hz) and inherent delays, which means that the RIS configuration may lag behind the actual position of the drone when it is updated, resulting in beam mismatch and performance degradation. Some studies have proposed a predictive control method based on kinematic observers and predictors (OPS/OPA) to compensate for system delays by predicting the user's future position and adjusting the RIS configuration in advance [6] .

4.2.3 Robustness and non-ideal factors

Real-world systems are plagued by numerous non-ideal factors, such as discretization of RIS phase shifts, hardware damage, and drone jitter and airflow disturbances. For example, research has shown that phase shift errors caused by drone jitter and airflow disturbances follow a von Mises distribution and significantly impact the system's confidentiality and energy efficiency. These non-ideal factors can severely impact the beamforming effectiveness of the RIS, leading to degraded communication performance and physical layer security (PLS) performance.

4.2.4 Standardization and evaluation system

Currently, the drone-RIS communication field lacks unified performance evaluation standards, simulation platforms, and hardware interface protocols. This hinders large-scale testing, verification, and commercial deployment of the technology. Industry companies, such as Rohde & Schwarz, have begun participating in 6G standardization projects and have proposed solutions to challenges such as RIS over-the-air (OTA) testing and performance measurement (e.g., EVM). Future work will require the establishment of a unified testing framework and metrics to promote the maturity of the technology.

5. Summary and Outlook

This article systematically reviews the converged communication of unmanned aerial vehicles (UAVs) and intelligent reflective surfaces (RIS) in low-altitude airspace. First, the necessity of UAV-RIS convergence is demonstrated, leveraging the complementary advantages of UAV maneuverability and RIS's low-energy reconfiguration capabilities to address bottlenecks such as high-frequency propagation obstruction and energy efficiency limitations. Second, the architectural evolution from single-UAV-RIS to multi-UAV cooperative networks is systematically reviewed, and the unique characteristics of A2G channels and RIS cascaded channels are analyzed. The article then summarizes recent advances in key technologies such as trajectory optimization, phase shift design, intelligent beamforming, and resource allocation, and quantifies the significant improvements in throughput, energy efficiency, security, and reliability achieved through experiments and case studies. Finally, the article identifies key challenges in this field, including the high overhead of cascaded channel estimation, the high complexity of real-time optimization, insufficient robustness under non-ideal conditions, and the lack of a unified standardization system. Overall, UAV-RIS communication, as a key supporting technology for 6G, holds significant theoretical significance and promising application prospects. However, breakthroughs in channel estimation, AI-driven optimization, and cross-domain network convergence are still needed to achieve truly integrated, all-domain intelligent communication across air, land, and sea.

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