REVIEW ARTICLE

RIS-Enabled UAV Communications and Sensing: Opportunities, Challenges, and Key Technologies

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Abstract

Unmanned Aerial Vehicles (UAV) play a critical role in the low-altitude economy; however, they face significant challenges in network coverage during transit. This paper investigates the characteristics and challenges of communication networks for UAV. First, we delineate typical scenarios, traffic characteristics, and the dual-layer heterogeneous network topology necessary for three-dimensional continuous coverage and network coexistence. Additionally, the paper addresses the channel characteristics and specific challenges faced by UAV Integrated Sensing and Communication (ISAC) networks, including the limitations of traditional APAA-based networks in terms of cost, complexity, and site selection. Subsequently, we present Reconfigurable Intelligent Surface (RIS)-assisted networks as a viable solution for enhancing UAV signal coverage. Key technical characteristics of RIS are discussed, along with design principles, antenna tilt design, and the application of new beam types. We also explore the implications of high-frequency bands and their absorption peaks on signal attenuation, as well as network architecture designs aimed at improving UAV signal coverage and facilitating network coexistence. Furthermore, the importance of standardization in RIS-based UAV networks is emphasized. We also present field trial results evaluating the effectiveness of RIS in improving UAV coverage. Finally, we outline future technology trends, highlighting potential advancements that could further optimize UAV communication systems.

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I. Introduction

The UAV (drone) market is projected to grow from USD 30.2 billion in 2024 to USD 48.5 billion by 2029, reflecting a compound annual growth rate (CAGR) of 9.9% during this period[1]. This growth is primarily driven by the continuous integration and upgrading of drones across diverse applications. Technological advancements, including enhanced power systems, sophisticated sensing technologies, and increased autonomy, have significantly expanded drone capabilities. Furthermore, the evolution of regulations facilitating the deployment of drones in civilian and commercial sectors has notably contributed to market expansion. The rising demand from industries such as delivery services, environmental surveillance, and monitoring plays a crucial role in this trajectory. The convergence of drone technology with emerging digital innovations continues to propel the industry's upward momentum. However, the coverage issues of Unmanned Aerial Vehicle (UAV) Integrated Sensing and Communication (ISAC) networks are technical bottleneck for the large-scale deployment of UAV.

UAV can be classified into various categories based on factors such as weight, size, wing configuration, and flight time, including small/micro-UAV and large UAV, as well as fixed-wing and rotor-wing types[1]. Each UAV type possesses distinct characteristics, making it suited to different application scenarios. A comprehensive overview of UAV classifications and their applications can be found in[2].

Wireless communication is one of the key technologies for unlocking the full potential of UAV, and as such, it has recently garnered unprecedented attention[3][4][5][6]. Currently, research and inquiries into UAV networks have surged. Several studies have been conducted, primarily focusing on developing a comprehensive understanding of UAV communication models. These investigations also address various aspects related to UAV applications, characteristics, challenges, and unresolved issues[7][8][9]. Additionally, some surveys propose solutions to specific requirements, such as security concerns, media access control protocols, quality of service (QoS), and routing protocols. The research cited in[7] provides an extensive survey on the use of UAV in wireless networks, offering a detailed examination of the fundamental trade-offs and significant challenges in UAV wireless networks.

A detailed review of Reconfigurable Intelligent Surfaces (RIS) technologies, including RIS-based UAV communication networks coverage solutions, will be presented.

RIS consists of passive reflective elements, each with a configurable reflection/refraction coefficient. This capability allows for intelligent coordination of the electromagnetic wave regulations, facilitating the reconfiguration of wireless channels. By coherently integrating desired signals and eliminating interference, communication throughput can be significantly enhanced without the need for additional active base stations (BS) or relays. It is also worth noting that RIS offers practical advantages, such as its lightweight nature, making it convenient to deploy on walls or fast-moving vehicles, thereby enabling a wide range of applications[10]. As a revolutionary technology, RIS effectively transforms the radio environment into an intelligent one, bringing substantial benefits to various sectors such as transportation, manufacturing, and smart cities. The usage of RIS has garnered attention as a promising technology for the development of 6G networks.

RIS, characterized by its low cost, low power consumption, and low complexity, is a promising technology in achieving effective network coverage for UAV with low cost.

Recent advancements have led to two promising avenues in UAV communications: UAV-assisted cellular networks and cellular-connected UAVs. Consequently, the integration of UAVs into cellular networks is recognized as a synergistic innovation beneficial for both UAV-related industries and cellular service providers. In this context, UAV communications can be categorized based on the role of the UAV within the network: 1) UAVs functioning as BSs (UAV-BS)[11] or relay to enhance signal coverage for ground communication or to facilitate terminal and target sensing, and 2) UAVs operating as communication terminals (UAV-UE)[12] or sensing objects that depend on terrestrial networks for coverage, particularly in low-altitude scenarios. Within these frameworks, UAVs are integrated into cellular systems, fulfilling dual roles as aerial communication platforms and users. This integration not only opens up a wide array of new business opportunities but also enhances the performance of three-dimensional (3D) wireless networks[13].

This paper will focus on the second category, specifically addressing the challenges and solutions associated with achieving low-altitude coverage for UAVs utilizing terrestrial networks[14].

The main contributions of this paper are as follows:

1. Thorough Analysis of UAV Signal Coverage Challenges: This paper provides a comprehensive examination of the key challenges associated with achieving low-altitude coverage for UAVs utilizing terrestrial networks.
    - Dual-Layer Heterogeneous Network Topology: We discuss a dual-layer heterogeneous network topology that integrates the terrestrial network coverage layer with the UAV low-altitude coverage layer, enabling three-dimensional continuous coverage. This multi-layer design mitigates inter-layer interference while presenting unique challenges for network coexistence.
    - Channel Characteristics and Challenges of UAV ISAC Networks: We identify two primary channel characteristics that distinguish low-altitude UAV networks from terrestrial networks: Line-of-Sight (LoS) channels and multipath fading. These unique channel properties introduce challenges related to sensing accuracy and interference management.
    - Challenges of Traditional APAA-Based Networks: Our analysis highlights the limitations of traditional phased array antenna-based networks for UAV signal coverage, focusing on issues of cost, complexity, and site selection. We propose two alternative approaches to address these limitations: enhancing existing BSs or deploying dedicated BSs for UAV coverage.
2. RIS-Based Solution for UAV Signal Coverage: We propose Reconfigurable Intelligent Surfaces (RIS) technology as a key solution to the challenges of UAV signal coverage. RIS technology has the potential to enhance UAV communication networks by improving signal propagation conditions and providing continuous coverage.
    - RIS-Enabled UAV Network Architectures: We explore various RIS-based UAV network architectures, including cell-free designs and networks utilizing non-diffracting beams, aimed at increasing spatial degrees of freedom, managing interference, and enhancing sensing accuracy.
    - Millimeter-Wave (mmWave) Communications for UAV: We discuss the potential of mmWave technology for UAV communications and sensing, reviewing typical findings and challenges while exploring RIS-based solutions to address these issues.
3. Standardization Aspects: We address the standardization considerations for UAV ISAC networks, emphasizing the need for scenarios and solutions that facilitate the integration of RIS with UAV communications.
4. Field Trial and Future Technology Trends: This paper presents a field trial conducted in China to demonstrate RIS-

based UAV coverage and outlines future research directions, including the variability of atmospheric ducting effects, emerging challenges in low-altitude UAV coverage, and the commercialization of RIS-based products.

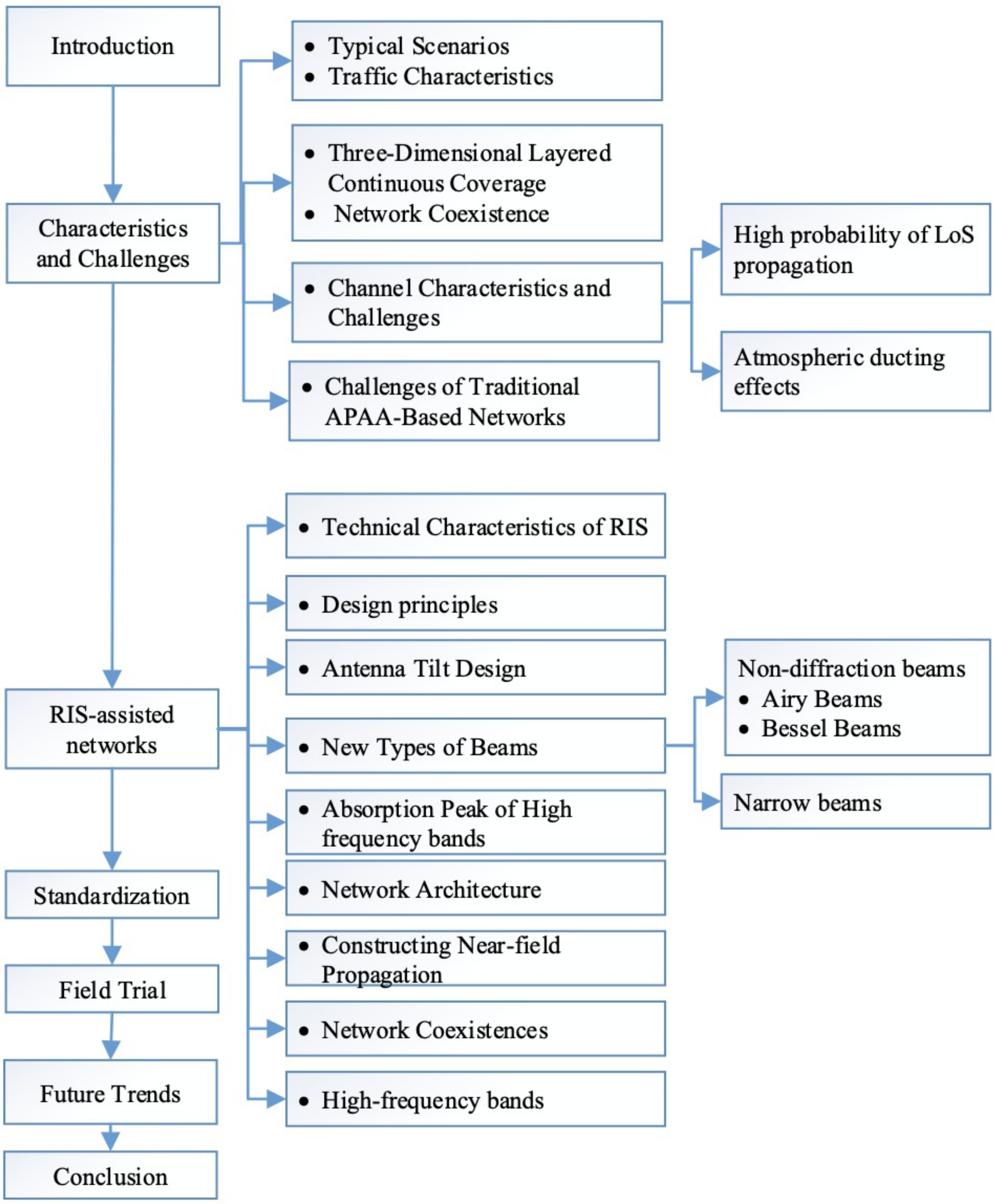

Figure 1. The organization structure of the survey

The organization structure of this paper is organized as follows (refer to**Fig. 1**). Section II elaborates on the main technical characteristics of UAV ISAC networks and the challenges they face. Section III presents a solution based on RIS technology to address UAV signal coverage. Section IV explores the standardization aspects of UAV ISAC. In Section V, the performance of the proposed solution is evaluated through field testing. Section VI outlines potential directions for future research. Finally, the conclusion is drawn in Section VII.

II. Characteristics and Challenges of Isac Networks

Although terrestrial wireless networks have been extensively studied for many years[15], their technologies and findings may not be directly applicable to future 3D wireless networks that incorporate both UAV, whether as aerial users or communication platforms and ground users, due to the significantly different operational environments. The new degrees of freedom introduced by UAV remain largely unexplored and may present unique challenges, while also offering the potential to enhance both communication and sensing capabilities.

A. Typical Scenarios and Traffic Characteristics of ISAC Networks for UAV

Compared to traditional terrestrial communication, UAV low-altitude coverage networks exhibit several novel characteristics. The characteristics of ISAC networks in UAV scenarios are as follows:

1. There is higher mobility and greater freedom in movement trajectories, posing challenges for channel estimation, feedback, beam tracking, beam switching, and cell handover.
2. Capacity requirements for UAV user equipment (UE)/sensing targets are lower than those for terrestrial coverage, accompanied by variations in service distribution.
3. ISAC networks for UAV represent typical ISAC scenarios, necessitating the simultaneous fulfillment of communication, sensing, and control service demands. The accuracy of sensing and positioning must exceed that of GPS/Beidou-based systems, which is crucial for justifying the adoption of new intermediate frequencies and mmWave bands. Furthermore, to achieve accurate target detection, sensing should concentrate on the main lobe of the echoed signal while suppressing side lobes, thereby prioritizing the main lobe for the coverage of sensing services.

In contrast to traditional terrestrial cellular networks, ISAC networks designed for UAV are distinguished by their specific application scenarios, introducing challenges that are entirely novel to conventional cellular systems.

B. Dual-Layer Heterogeneous Network Topology for UAV: Three-Dimensional Layered Continuous Coverage and Network Coexistence

This section aims to analyze the fundamental differences in network coverage between terrestrial networks and low-altitude networks, with a particular focus on the challenges of joint coverage optimization and the coexistence of multi-layer coverage networks.

The UAV dual-layer heterogeneous network topology can integrate the terrestrial network coverage layer with the UAV low-altitude network coverage layer, thus achieving a three-dimensional continuous coverage[16]. The terrestrial network coverage layer relies on traditional cellular network, with appropriate antenna down-tilts to optimize the signal reception of terrestrial users. In contrast, the UAV low-altitude coverage layer requires antennas up-tilts to enhance LoS transmission paths and provide enough coverage in low-altitude areas. This multi-layer design significantly reduces the coupling between the two coverage layers effectively mitigates inter-layer interference, and enhances overall network performance.

Despite the numerous advantages of the multi-layer design, the joint optimization of terrestrial and low-altitude coverage layers has several challenges. The first one is to ensure that the solution is cost-effective. The antennas down-tilts designed for traditional cellular networks to cover mobile users are not inherently suitable for UAV flying at low-altitude. Consequently, additional deployment of specialized up-tilt antennas is needed. This not only increases the hardware costs but may also boost the power consumption due to the extra complexity of the antenna system. Thus, there is an urgent need to balance the revenue growth from the sensing related services and the cost overflow of the network construction plus the operation. Second, the deployment complexity associated with the joint optimization is a difficult problem. The introduction of dual antenna systems not only adds the weight and size to the equipment, imposing higher payload requirements on UAV, but also introduces challenges in site selection. The joint optimization should consider the effective coverage while optimizing BS layout, minimizing redundant construction, and reducing the deployment costs.

In addition to the coupling between terrestrial and low-altitude coverage layers, network coexistence issues between low-altitude UAV coverage layers and mid-to-high altitude coverage layers (such as civil aviation and low Earth orbit satellites) should also be addressed[17]. Since UAV low-altitude coverage layers primarily rely on LoS transmission, the signal attenuation as a function of propagation distance is relatively slow, which may lead to spectrum competition or interference with mid-to-high altitude aircraft and other networks. Therefore, joint optimization strategies should consider network coexistence factors to ensure harmonized coexistence between network layers.

In summary, the research on UAV low-altitude coverage need to consider various factors such as cost-effectiveness, deployment complexity, and network coexistence in a comprehensive manner.

C. Channel Characteristics and Challenges of UAV ISAC Networks

Compared to terrestrial coverage, ISAC networks for low-altitude UAV exhibits two primary channel characteristics: high probability of LoS propagation and significant effect of atmospheric ducting. Both characteristics result in small pathloss, which is beneficial for wireless signal transmission. However, they may also lead to increased inter-cell and inter-network interference, as the range of signal propagation becomes difficult to control causing a divergence from the design principles of cellular networks. A fundamental principle in the cellular network design is the effective control of coverage areas between neighboring BSs or sectors to allow small reuse factor and improve the system spectral efficiency.

(1) High probability of LoS propagation

When drones operate in the air, they are typically not obstructed by ground obstacles such as buildings and trees. This leads to a predominance of LoS channels. The LoS dominated air-ground channels inherent to UAV at high altitudes lead to smaller path loss due to less severe shadowing and multi-path fading[18]. A study considers three-dimensional mobility and LoS channel properties for cellular-connected UAV is presented by[19]. They defined the essential challenges for them and introduced the key performance indicators with analytical models by considering several performance outputs.

In such scenarios, shadows from terrestrial obstacles become negligible, and the pathloss aligns closely with the free space propagation model which can be described by the following formula:

$$L_{fs}(dB) = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right)$$

where d is the signal propagation distance, f is the signal frequency, and c is the speed of light in vacuum.

This formula indicates that the primary factors affecting free-space propagation are the propagation distance and the carrier frequency. As the propagation distance increases, the path loss also increases. Similarly, higher signal frequencies result in greater path loss. High-frequency signals, due to their shorter wavelengths, are more susceptible to the blocking by small objects when propagating near the ground. However, in free-space propagation, this effect is minimal. **Fig. 2** compares the free-space pathloss (accounting atmospheric and rain-induced attenuation) and the pathloss in terrestrial urban environment. The conditions are set as follows: transmitter power is assumed to be unit 1, operating in the mmWave 28 GHz frequency band, with 64 transmit antennas and 16 receive antennas. The transmitter employs optimal beamforming, and the receiver is equipped with the optimal receiver. It can be observed that in the signal attenuation of LoS channels is 20~40 dB lower than that in ground urban channels, and their difference becomes wider as the distance increases.

In terrestrial wireless communication systems, buildings, vegetations, and other obstacles would cause the reflection, refraction, diffraction, scattering of electromagnetic waves, which significantly limit the range of propagation. This makes the cell coverage more localized and manageable, restricting the signal within the target coverage area (cell/sector). In contrast to terrestrial environments, where signals encounter various impediments, free space propagation allows signals to travel longer distances and cover wider areas. Furthermore, environments dominated by LoS channels are more favorable to sensing-related services. Despite the presence of atmospheric and rain attenuation, the propagation is still quasi-free-space and the coverage is still almost uncontrollable, posing significant challenges to the communication aspect of UAV. For example, it can result in a higher level of co-channel interference between adjacent cells, leading to reduced SINR, frequent ping-pong effects during handover. Moreover, for propagation environments dominated by the LoS propagation, the rank of the MIMO channel is 1 under far-field conditions, making it difficult to achieve spatial multiplexing gains.

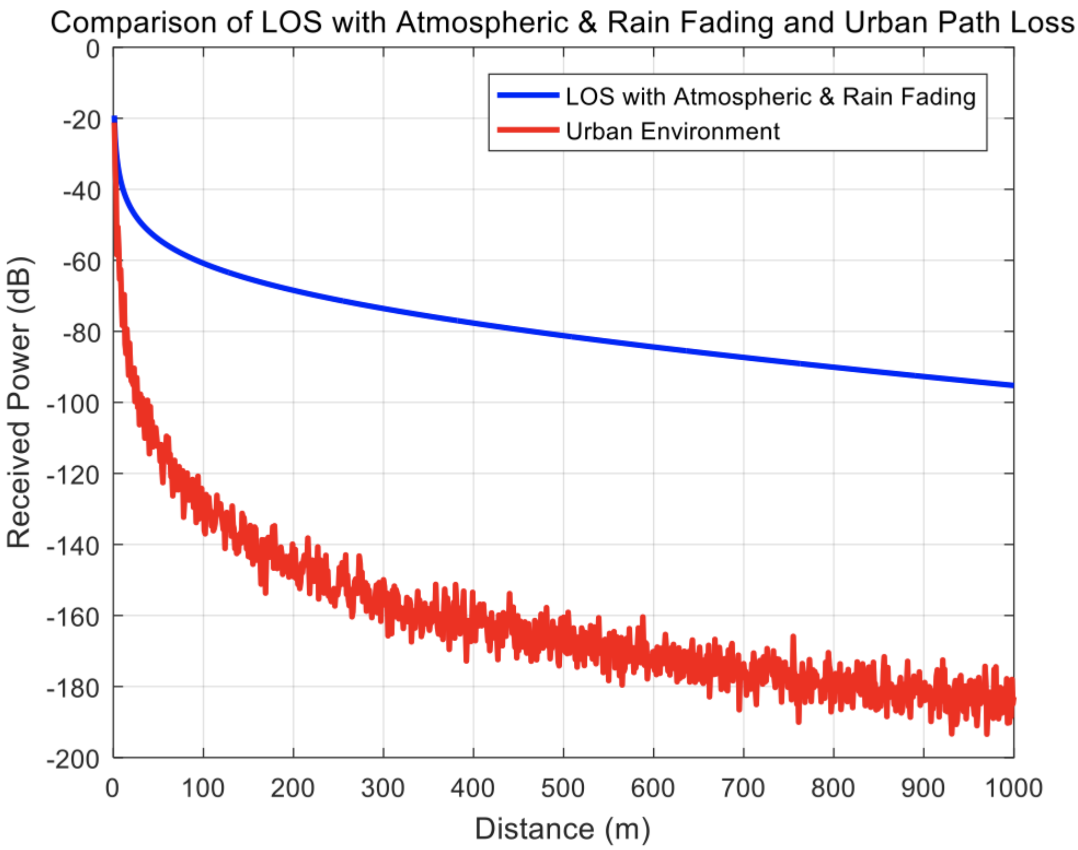

Figure 2. Path loss comparison between LoS and Urban channel

(2) Atmospheric ducting effects leading to long-distance propagation

Atmospheric ducting is a unique phenomenon where electromagnetic waves propagate within a specific height range due to changes in the atmospheric refractive index. This results in the reflection and refraction of EM waves, causing them to travel along the atmospheric layer in a manner similar to a waveguide. The ducting phenomenon occurs when the angle of incidence of electromagnetic waves is less than the critical angle, leading to total internal reflection at the interface. In the case of atmospheric ducting, the angle of incidence typically needs to be close to horizontal, resulting in much lower path loss compared to normal atmospheric environments[20][21].

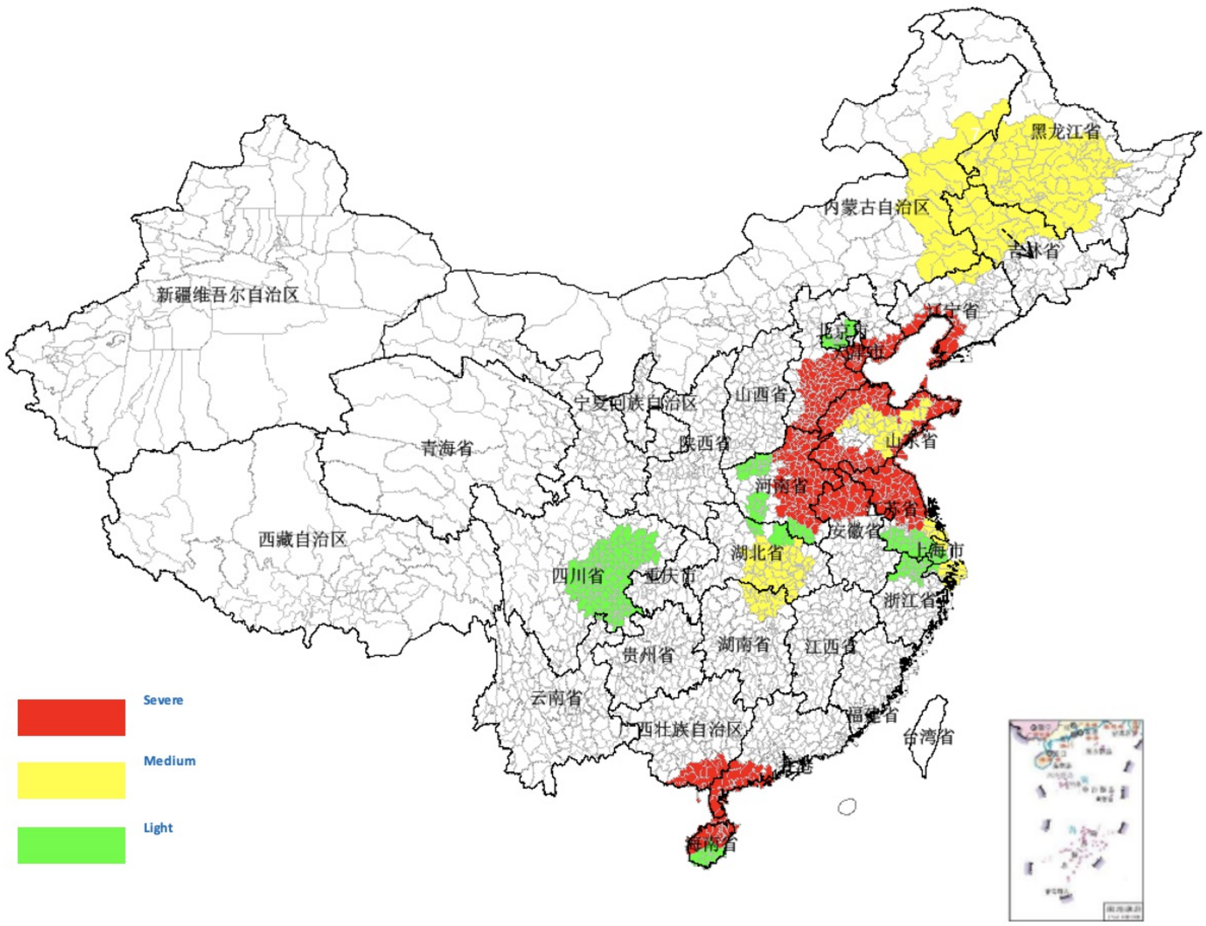

Figure 3. Deployment of tropospheric ducting in China (TD-LTE networks)

Fig. 3 illustrates the impact of atmospheric ducting phenomena measured in China Mobile's TD-LTE networks. The figure shows that tropospheric ducting is observed in the Jianghan Plain, the coasts of Hainan Island and Bohai Bay, and especially in the North, Central, East, and Northeast China Plains. The website[2] provides global atmospheric duct forecast information for the next 7 days, with forecasts provided at 3-hour intervals for the first 36 hours and 6-hour intervals for the remaining 6 days. In wireless communication systems affected by the atmospheric ducting phenomenon, the distance between the victim and the aggressor ranges from 64 km to 400 km, typically remaining within 150 km in most inland areas, while occasionally exceeding 300 km in coastal regions[21].

This phenomenon can lead to much longer propagation distances than predicted by the free-space propagation model, expanded UAV's signal coverage area and increased inter-cell interference[22].

Parabolic equation (PE) methods derived from Maxwell equations are widely utilized to characterize the atmospheric ducting channels[23]. Path loss in the atmospheric ducting channel can be obtained based on the PE methods by

$$PL = 20\lg\left(\frac{4\pi}{|u(x,z)|}\right) + \lg(d) - 30\lg(\lambda) \qquad (2)$$

where $u(x, z)$ is the reduced field component, x and z are respectively the horizontal and vertical axes representing range and altitude, d is the range from the transmitter and λ is the wavelength[24].

Based on the conditions for atmospheric ducting phenomena, macro-BSs used in traditional terrestrial coverage cellular networks, which have relatively small antenna down-tilt angles, may meet the conditions for atmospheric ducting. In contrast, low-altitude coverage networks designed for UAV operations, which employ up-tilted antennas, are more likely to satisfy the conditions for atmospheric ducting. Consequently, the impact of atmospheric ducting on low-altitude coverage networks is more pronounced.

Similar to the effects of free-space fading, although atmospheric ducting can extend the transmission range of wireless signals, which is advantageous for signal coverage in specific scenarios, such as long-distance coverage over the sea, it poses challenges for conventional Time Division Duplex (TDD) systems[22]. Atmospheric ducting can result in uplink and downlink cross-link interference (false detection) between extremely distant BSs and multiple sensing peaks (false alarms) due to signals from remote cells.

The above analysis reveals significant differences in the interference effects caused by the two types of channel characteristics. Specifically, quasi-free-space fading in LoS channels primarily results in co-channel interference between adjacent cells. In contrast, atmospheric ducting leads to extremely long-distance wireless signal propagation, which consequently causes inter-link interference in Time Division Duplex (TDD) systems.

D. Challenges of Traditional APAA-Based Networks For UAV (Cost, Complexity, and Site Selection Challenges)

To extend coverage to high-altitude UAV while maintaining traditional ground network coverage, it is necessary to deploy additional BSs equipped with phased array antennas angled upward to ensure continuous coverage for high-altitude UAV.

There are two possible approaches to achieve this extended coverage:

Approach 1: Upgrading existing BSs

In this approach, existing BSs are upgraded with additional phased array antennas facing upward for high-altitude coverage. This method can reduce the number of new BSs required, thereby lowering the costs and minimizing the need for additional sites. However, the added active phased array antenna (APAA) still entails significant costs. Moreover, deploying these new antennas on existing BSs introduces additional complexity, such as increased weight, volume, and power supply requirements, which can pose challenges to the existing infrastructure.

Approach 2: Dedicated BSs for UAV coverage

Alternatively, dedicated BSs specifically designed for high-altitude UAV coverage can be deployed, without reusing existing BSs. These dedicated BSs feature APAAs facing upward to achieve the desired coverage. This method allows for optimized deployment without the constraints of existing BS site. However, deploying a new set of BSs for UAV coverage involves higher costs and poses greater challenges in site selection.

Based on the analysis of the two typical implementation approaches for APAA coverage using traditional BSs, it is seen that while both methods have their advantages, they each face unique challenges related to cost, complexity, and site selection.

In summary, the characteristics and challenges of UAV networks are reflected in the following aspects:

1. Compared to ground coverage, low-altitude coverage exhibits high mobility and different traffic distribution, making it a typical application scenario for ISAC.
2. UAV networks represent a dual-layer heterogeneous network topology that requires three-dimensional, continuous coverage, posing challenges for multi-layer network coexistence.
3. Challenges arising from UAV channel characteristics include: LoS channels (free-space fading plus atmospheric and rain-induced fading), difficulty in controlling cell coverage areas, and potential increased co-channel interference between adjacent cells. UAV low-altitude coverage antennas must use upward tilts, which, compared to traditional downward tilts, may result in more significant atmospheric ducting phenomena. This can lead to cross-link interference between extremely distant cells in TDD systems.
4. Challenges associated with traditional APAA-based BSs include issues related to cost, complexity, and site selection.

III. RIS-Assisted Networks for UAV Signal Coverage

RIS, with their unique technical advantages, have the potential to emerge as strong candidates for achieving cost-effective signal coverage for UAV. Extensive research has been conducted on RIS in several system configurations, as seen by studies referenced in sources[25][26]. The device has the capability to be installed on land in order to facilitate communications for UAV, or it can be affixed to UAV for communications on the ground[27]. This section will explore various innovative RIS-based approaches, including antenna tilt design, beam design, the use of high-frequency millimeter waves or terahertz absorption peaks, and network architecture optimization. Each approach offers unique advantages and is suited to specific scenarios, and the theoretical foundations, design concepts, and implementation details will be examined in detail.

A. Technical Characteristics of RIS

RIS are best known for their low cost, low power consumption, low complexity, and ease of deployment. These advantages allow RIS to demonstrate extensive application potential in areas such as wireless channel improvement, RIS-based phased array antenna, and information modulation[28]. Furthermore, with its ultra-large antenna aperture, RIS can easily form a ubiquitous near-field propagation environment for future 6G networks[29][30].

1) Role of RIS in Future Networks: Auxiliary vs. Fundamental Network Element

With the continuous evolution of network technologies, each generation of networks has introduced unique service characteristics and signature technologies. The 4G era is characterized by mobile broadband connectivity with OFDM and

MIMO as signature technologies, In the 5G era, the Internet of Everything and Massive MIMO are the signature technology. For 6G, integrated sensing and communication, space-ground integration, and ubiquitous intelligence, RIS, new multiple access and other candidate technologies (such as AI-based X) have the potential to become the signature technologies.

- Auxiliary Network Element Role: In specific scenarios, RIS acts as an auxiliary network element, enhancing performance and providing additional improvements to existing networks.
- Fundamental Network Element Role: In most cases, RIS serves as a fundamental network element, taking into account technology maturity, cost, power, and complexity constraints. It provides essential capabilities for the practical implementation and large-scale commercialization of 6G networks, akin to "offering timely assistance," especially in key functionalities like virtual BSs.

2) Typical Application Scenarios and Potential Opportunities of RIS in 5G-A and 6G Networks

- 5G-Advanced (5G-A) Scenarios: Enhancement of low-frequency coverage (Auxiliary): As an auxiliary network element, RIS can extend the coverage l, effectively improving network performance.
  Enabling continuous coverage for mmWave networks: In this scenario, RIS acts as a fundamental network element, ensuring continuous and reliable coverage for mmWave networks in power-limited environments.
- 6G Network Scenarios: Enabling continuous coverage in mid- to high-frequency and mmWave bands: RIS, as a fundamental network element, plays a critical role in ensuring continuous coverage of mid- to high-frequency and mmWave signals in 6G networks.
  Enabling ubiquitous sensing and positioning: Through flexible RIS configuration, 6G networks can provide broader capabilities of sensing and positioning with high precision with.
  RIS-based phased array antennas: The introduction of RIS technology provides innovative implementation for phased array antenna design in 6G networks, fostering further advancement in antenna technologies.
  Enabling ubiquitous near-field communication: The deployment of RIS extends the coverage of 6G networks, especially in near-field communication

In summary, the role of RIS technology in future networks will be flexibly adjusted based on the specific demands of application scenarios. An RIS can serve as an auxiliary network element to enhance network performance or as a fundamental network element to support core capabilities of radio networks, injecting new momentum into the development of 6G and future networks.

B. RIS-Based UAV ISAC Networks: Design Principles

To effectively address the challenge of UAV signal coverage, the following design principles should be adhered to:

Ensure Continuous Coverage: to guarantee seamless signal coverage within a target area to avoid blind spots of signals.

Constrain propagation areas: to limit the signal propagation in non-target areas to reduce interference and increase frequency reuse.

Network Coexistences: to have Three-layer coverage networks on the ground (e.g. traditional UE and sensing targets), low altitude (e.g., drones), and mid to high altitude (e.g., commercial aircraft)

Reduce Cost and Complexity: Consider the costs associated with deployment, engineering complexity, and site selection challenges.

Appropriate Access Capacity: the RIS can only regulate channel propagation conditions, enhancing throughput and sensing accuracy; however, it cannot increase terminal access capacity or sensing capacity. The terminal access capacity and sensing capacity are dependent on active BSs.

C. RIS-Based UAV ISAC Networks: Antenna Tilt Design

Antenna tilt angle design is an effective technique for optimizing signal propagation, mitigating interference, and improving coverage by adjusting the elevation and depression angles of the antenna. In the context of UAV signal coverage, a carefully designed tilt angle can significantly enhance both signal range and quality, particularly in complex aerial propagation environments.

In current cellular networks, ground-based BS antennas are typically down-tilted, with their main lobes directed towards the ground to optimize coverage for terrestrial users. UAV flying above these BSs, however, are predominantly served through the side lobes, posing new technical challenges for simultaneously providing reliable service to both UAV and ground users[31][32][33][34].

Consequently, the conventional down-tilted BS antennas, designed primarily for ground coverage and inter-cell interference suppression, must be reconfigured. Studies conducted by 3GPP confirm that UAV receive weak signals from terrestrial BSs, necessitating further research and development to support aerial users effectively[35][36]. The authors in[37] highlighted the varying altitudes of UAV flight, while in[37][38], the importance of factors such as antenna tilting and 3D coverage models was addressed. A comprehensive study on the performance of various antenna deployments for cellular-connected UAV scenarios can be found in[39].

The two deployment approaches for achieving low-altitude UAV coverage using RIS are discussed below.

1) Approach 1

The BS antennas employ traditional down-tilt configurations, while the non-collocated RIS regulates the electromagnetic wave propagation path and performs beamforming to direct signals towards low-altitude UAV, i.e., the RIS manages channel control to facilitate upward signal propagation. By utilizing 3D passive beamforming via RIS reflections to serve UAV in flight, the communication links between ground nodes and UAV can be significantly enhanced, reducing the need for extensive modifications to the existing ground BS antenna configurations.

Regarding the multiplicative fading in the RIS-cascaded channel, the primary channel follows a LoS path (as the RIS-UAV cascaded channel can easily establish LoS), primarily modeled by free-space fading. Consequently, signal attenuation increases more gradually with distance, enabling effective signal coverage for low-altitude UAV, even under multiplicative fading conditions.

The BS can simultaneously achieve both ground and low-altitude UAV coverage using down-tilt antennas, thereby eliminating the necessity for additional upward-tilt antenna installations. To address the interference encountered during upward signal propagation—namely, neighboring cell interference from free-space fading and cross-link interference from TDD systems due to waveguide effects—the RIS-controlled beam should be angled as upward-tilting as possible. This minimizes horizontal propagation interference and avoids incidence angles that could trigger total internal reflection conditions associated with waveguide effects.

High-density deployment of RIS is required to suppress interference effectively. To achieve this, RIS beams should be as vertically aligned as possible, which reduces the coverage area per RIS. Consequently, more RIS units are needed to ensure continuous UAV coverage. In[40], the potential of RIS to enhance cellular communications for UAV was investigated, with received signal power gain analyzed as a function of UAV height and various RIS parameters, including size, altitude, and distance from the BS. The study demonstrated that for a UAV hovering 50 meters above ground, a 21 dB received power gain could be achieved with a properly deployed RIS comprising 100 passive elements, based on 3GPP ground-to-air channel models. Furthermore, it was shown that the optimal deployment altitude of the RIS decreases as the RIS-BS distance increases, ensuring effective reflection of signals from the BS.

2) Approach 2

Building on Method 1, which utilizes relay-like RIS for UAV coverage, an additional upward-tilted antenna array is configured at the BS to further meet UAV coverage requirements. This involves equipping the BS with both downward-tilted and upward-tilted antenna arrays. The upward-tilted array leverages RIS-based antennas, which take advantage of RIS's benefits, such as low cost, low power consumption, low profile, and low complexity. While, Similar to Method 1, the relay-like RIS deployed in the propagation environment controls the electromagnetic wave propagation path and beamforming for the downward-tilted antennas, directing the enhanced signal to low-altitude UAV. In the configuration of Method 2, two types of RIS are deployed: RIS-based phased array antennas mounted on the BS, and relay-like RIS units deployed in the propagation environment for channel regulation.

- Beam Upward-Tilt Constraint: The tilt angles of the beams from both the BS and RIS for UAV should be as vertical as possible, thereby reducing the coverage area of the BS and each RIS.
- Low-Power Transmission for Upward-Tilted Antennas: To mitigate interference and coexistence issues, the upward-tilted antennas at the BS are configured for low-power transmission.
- Co-location of RIS-Based Upward-Tilted Antenna Arrays: The RIS-based upward-tilted antenna arrays can be co-located with the BS, overcoming challenges related to the weight, size, and power consumption of traditional APAA systems.
- High-Density RIS Deployment Requirement: A sufficiently dense RIS deployment is necessary to ensure continuous

UAV coverage. The unique characteristics of RIS, including low cost, low power consumption, and low complexity, allow for economically efficient, continuous UAV network coverage.

In summary, to address interference issues, a sufficiently dense deployment of RIS is essential. Considering the cost and complexity of new RIS installations, employing RIS in existing sub-6 GHz 5G networks is not economically viable. However, for new mid-band and mmWave networks, the relative cost and deployment complexity of RIS are manageable, making the combined optimization of BSs and RIS a more favorable approach.

D. RIS-Based UAV ISAC Networks: New Types of Beams

The primary objectives of beam design are to achieve efficient coverage of the target area by adjusting the direction and shape of the beam, while ensuring rapid signal attenuation in non-target areas to minimize interference. For UAV signal coverage, a well-designed beam can significantly improve both the range and quality of signal coverage, especially in the complex aerial propagation environments discussed in Section II.

The fundamental design concept of the new beam focuses on restricting the coverage area and can be outlined as follows:

Beam Focusing: Concentrating the beam within the target area to avoid excessive coverage. It is essential to maintain the signal strength within the target area to meet communication requirements. Beam focusing can be realized through the use of directional or array antennas.

Rapid Diffraction: Outside the target area, the beam should quickly diffract, leading to a reduction in signal strength. By designing an appropriate beam shape, the signal can rapidly attenuate after leaving the target area, thereby minimizing interference with other regions.

Narrow Beams: Utilizing a super-large aperture RIS array to generate narrow beams reduces the likelihood of spatial overlap, effectively mitigating interference.

The utilization of RIS with ultra-large antenna apertures to control novel beam patterns can be effective in mitigating interference in UAV networks. Diffraction-free beams (e.g., Bessel beams, Airy beams) and narrow beam characteristics can serve as innovative beam patterns for interference suppression in UAV networks.

1) Non-diffraction beams

Diffraction-free beams[41], with their superior spatial characteristics, represent a novel approach for UAV coverage, and RIS with extremely large antenna apertures is a key candidate technology for realizing such beams.

- Airy Beams. The Airy beam, known for its non-diffracting characteristics, can maintain high intensity within the target area while rapidly diffracting and scattering beyond it.
- Other types of diffraction-free beams. E.g., beamforming based on Bessel functions can concentrate signals in the target coverage area, reducing interference and leakage caused by signal diffraction to other angle areas.

The electric field distribution of the Airy beams is given by the formula:

$$E(x,z) = Ai\left(\frac{x - z^2}{z_0^2}\right)e^{i\left(\frac{xz}{2z_0^2} + \frac{z^3}{3z_0^3}\right)}$$

where $E(x,z)$ is the beam field strength, Ai is the Airy function, x and z are spatial coordinates, and z_0 is a beam parameter.

- The beam's direction turns towards the vertical after passing through the target area: After the beam passes through the target area, it should propagate upwards, reducing the horizontal transmission distance. Adjusting the beam's direction to propagate vertically after the target area helps prevent interference caused by horizontal transmission.

The directional gain of the beam is defined by the formula:

$$G(\theta) = G_0\left(\frac{\sin(N\pi\sin(\theta)/\lambda)}{N\sin(\pi\sin(\theta)/\lambda)}\right)^2$$

where $G(\theta)$ is the gain in the direction θ, G_0 is the maximum gain, N is the number of antenna elements, and λ is the wavelength.

- Composite Beams: Utilizing multiple beams in combination allows for more flexible control over signal coverage and interference. For example, two Airy beams with opposite phases can be combined to quickly diffract and diffuse energy after passing through a UAV. The electric field distribution for a multi-beam design is given by:

$E_{total}(x,z) = \sum_n w_n E_n(x,z)$ where $E_{total}(x,z)$ is the total electric field distribution, w_n is the weight of the nth beam, and $E_n(x,z)$ is the electric field distribution of the nth beam.

2) Narrow beams

In[42], UAV can fly much higher than BSs and buildings. Therefore, they tend to be visible to more cells. On the other hand, the communication between UAV and a BS may cause potential interference to other cells. Since the channels between UAV and BSs are in general dominated by LoS paths with small angle spread, the inter-cell interference can be effectively reduced by directional beamforming, which is also the enabling technique of mmWave communications. However, the beam width needs to be carefully designed as narrow beams may lead to heavy training overhead for beam alignment, whereas wider beams may cause high interference.

3) General Steps for Beam Design in UAV Coverage

Designing an effective beam pattern is essential for optimizing UAV coverage. The general steps involved in this process are as follows:

1. Determine Beam Parameters: Define the beam width, direction, and shape based on the coverage requirements of the

target area. For applications requiring broader coverage, a wider beam may be selected, while for high-intensity coverage, a narrower beam is more suitable.

2. Design Beam Shape: Customize the beam shape according to the size and contours of the target area. For example, an Airy beam, known for its curved propagation characteristics, can address specific coverage needs, whereas a highly directional narrow beam is ideal for precise spatial coverage.
3. Adjust Beam Direction: Align the beam's propagation direction with the location of the target area. In aerial coverage scenarios, enhancing vertical propagation and minimizing horizontal components is often preferable.
4. Optimize Beam Combination: Use a combination of multiple beams to achieve flexible coverage. This approach enables coverage of various target areas and helps control interference by integrating beams with different directions and shapes.

By carefully designing beam shapes and spatial propagation characteristics, signal coverage can be optimized, improving communication quality and overall system performance across diverse applications.

Beam design plays a pivotal role in optimizing UAV signal coverage. By fine-tuning the beam's direction and shape, effective coverage of the target area can be achieved, while minimizing signal propagation in non-target areas to reduce interference.

E. RIS-Based UAV ISAC Networks: Absorption Peak of High Frequency Bands

The absorption peak bands exhibit high atmospheric absorption, leading to rapid signal attenuation with distance. Leveraging this attenuation characteristic allows for effective suppression of the signal coverage area.

In modern wireless communication systems, due to the scarcity of spectrum resources, the management of interference is critical. The mmWave and terahertz (THz) bands, with their extensive spectrum bandwidth, are considered key technologies for meeting future communication demands. Specifically, the mmWave and THz bands in the 30 GHz to 300 GHz range have garnered attention due to their unique propagation characteristics. Among these are certain absorption peak bands, where atmospheric absorption properties cause the signal to attenuate rapidly over distance. This provides a novel approach to managing coverage and interference in target areas.

1) Physical Properties of Absorption Peak Bands

The absorption peak bands exhibit significant absorption characteristics in the atmosphere. Molecules like oxygen and water vapor in the atmosphere exhibit strong absorption in these bands, leading to rapid signal attenuation with propagation distance. For example, frequencies around 60 GHz and 183 GHz are typical absorption peak bands[43][44]. This absorption phenomenon can be represented by the following formula:

$$P(d) = P_0 e^{-\alpha d}$$

where $P(d)$ is the signal power at a distance d, P_0 is the initial transmitted power, and α is the atmospheric absorption coefficient, which depends on frequency and atmospheric conditions.

To further explore the physical properties of the absorption peak bands, the following aspects can be considered:

Absorption Mechanism: In the high-frequency mmWave and THz bands, the interaction between electromagnetic waves and atmospheric molecules leads to significant absorption. The primary absorption mechanisms include transitions of vibrational and rotational energy levels, which absorb the energy of electromagnetic waves, resulting in signal attenuation. For instance, the 60 GHz and 183 GHz bands correspond to absorption peaks for oxygen and water vapor molecules in the atmosphere.

Absorption Coefficient: The absorption coefficient is a key parameter describing the absorption characteristics of electromagnetic waves in the atmosphere. It depends on frequency, meteorological conditions (such as temperature and humidity), and atmospheric composition. The absorption coefficient can be obtained through experimental measurements and theoretical calculations. Typically, the values of α at 60GHz and 183GHz bands are 0.15km^{-1} and 1.5km^{-1}, respectively, reflecting the absorption intensity at different frequencies.

2) Constraining Coverage Area

Utilizing the characteristics of absorption peak bands, the coverage area can be precisely constrained by adjusting transmission power and selecting appropriate frequencies, thus achieving optimized communication system design.

To effectively constrain the signal coverage area, optimization can be approached from two perspectives. On one hand, adjusting the transmission power can alter the radius of the signal coverage area. In practical applications, the transmission power can be dynamically adjusted based on the size of the designated area and the required coverage range, allowing for flexible coverage control. On the other hand, selecting an appropriate frequency is pivotal. By selecting suitable absorption peak bands, atmospheric absorption characteristics can be harnessed to manage the signal coverage area. Higher frequencies, such as 183 GHz, coupled with higher absorption coefficients, lead to smaller coverage radius, making them suitable for precise coverage of small areas. Conversely, lower frequencies, for example, 60 GHz, with lower absorption coefficients, result in larger coverage areas, which are suitable for relatively extensive regions.

F. RIS-Based UAV ISAC Networks: Network Architectures

Network architecture plays a critical role in improving the coverage and quality of UAV signals. By optimizing cell layouts, utilizing distributed antenna systems, and incorporating RIS technology, efficient signal coverage can be achieved while minimizing inter-cell interference.

As discussed in Section 2, UAV network coverage is structured as a dual layer heterogeneous network topology, which integrates the ground network coverage layer with the low-altitude UAV network coverage layer to enable continuous 3D coverage. Additionally, compared to ground coverage, the traffic distribution in low-altitude UAV coverage is notably different. The RIS-based network architecture must be optimized to account for the heterogeneous nature of this two-tier topology and traffic distribution.

Unlike ground coverage, the density of low-altitude UAV terminals is relatively low, meaning the per-unit-area capacity/access demand is reduced. Moreover, as previously mentioned, low-altitude UAV coverage, due to its quasi-free-space fading model, results in strong coupling between neighboring cells. If the issue of neighboring cell relations is not properly addressed, it could lead to significant inter-cell interference and frequent handovers between cells.

To overcome the issues of inter-cell interference and handover in traditional cellular networks, the so-called cell-free (CF) massive MIMO network infrastructure has been proposed as a beneficial embodiment of the general distributed massive MIMO concept[45], where cell boundaries do not exist. In cell-free systems, a large number of geographically distributed antennas jointly serve a smaller number of UEs via a fronthaul network and a central processing unit (CPU), all operating on the same time-frequency resource. The cell-free massive MIMO concept builds on earlier distributed antenna systems (DAS)[46], network MIMO, and coordinated multipoint (CoMP)[47], all of which belong to the distributed antenna network architecture category. Due to its inherent advantages, cell-free massive MIMO is regarded as a key enabling technology for 6G networks.

With its unique advantages, the cell-free architecture is an ideal candidate for realizing UAV coverage within a two-tier heterogeneous network topology. The cell-free framework enables flexible coordination among a larger number of access points (APs) to support a broader UAV coverage area while using fewer APs to cover smaller ground areas. This approach effectively reflects the dual-layered or heterogeneous network structure. Additionally, since the low-altitude UAV network's coverage area is constrained by the beam angles of each antenna array, multi-node cooperation is required to ensure continuous coverage of the target area, making the cell-free architecture a natural choice.

Since the advent of 4G LTE, CoMP technology, the predecessor to cell-free, has been a topic of discussion and was integrated into the 4G LTE standard, though it has not yet been widely commercialized. While CoMP was considered during the development of the 5G standard, current implementations only involve non-coherent CoMP JT. The primary advantage of CoMP lies in coherent CoMP JT, yet the benefits achieved through non-coherent CoMP JT are limited, posing challenges for broad commercial applications. One major obstacle to implementing coherent CoMP with traditional active phased arrays is the complex issue of antenna reciprocity calibration between different APs[48]. Similar to CoMP, cell-free systems face the same challenge of antenna reciprocity calibration when implementing coherent transmission. However, RISs, which utilize passive control, do not face the inherent challenges of antenna channel reciprocity calibration, providing a feasible solution for enabling coherent transmission in cell-free networks[49].

Furthermore, in[49], the potential initial phase differences between different RIS elements are addressed, proposing that coordination by the BS can align the phase relationships between multiple RIS units, thereby enabling coherent transmission in cell-free systems. Combining cell-free and RIS technologies can significantly enhance the signal coverage and quality of UAV communication systems, thereby improving overall system performance.

G. RIS-Based UAV ISAC Networks: Constructing Near-field Propagation to Increase Spatial DoF

The LoS channel of UAVs is advantageous for sensing, albeit at the cost of reduced spatial multiplexing gain in MIMO systems. RIS, with its advantages of low cost, low power consumption, and flexible deployment, presents a potential solution for achieving continuous coverage in the new mid-frequency and mmWave bands. For example, reusing existing 5G BS sites (i.e., deploying mmWave BSs with a density similar to or slightly higher than that of existing sub-6 GHz BSs) and densely deploying RIS between BSs can enable cost-effective continuous coverage in these frequency bands. In the mid-to-high frequency bands, the combination of RIS's ultra-large aperture and dense deployment significantly enhances near-field characteristics, thereby increasing spatial degrees of freedom and improving spatial multiplexing gain[50].

The combination of the ultra-large aperture of RIS and its dense deployment in the mid-to-high frequency range will create ubiquitous near-field propagation, supporting broadband high-throughput communication and enabling continuous coverage for high-precision sensing.

H. RIS-Based UAV ISAC Networks: Network Coexistence

With related to spectrum management for UAV operations is explored in[51], identifying suitable management schemes aligned with UAV features and spectrum requirements. assumes coexistence with prevalent wireless technologies that occupy the spectrum. It also presented the rulings from policymakers and regulators and discussed the operation bands and radio interfaces.

The coexistence issues between low-altitude and mid-to-high altitude coverage involve coordinating different flight altitudes, communication requirements, and coverage areas. To ensure efficient and interference-free coexistence of these networks, in-depth research is needed in areas such as spectrum management, interference mitigation, and network architecture optimization.

Layered Coverage: Given the significant differences in service demands between low-altitude and mid-to-high altitude coverage, adopting a layered network coverage approach is the most suitable choice.

Network Coexistence: The altitude differences and frequency overlaps between these layers may lead to mutual interference, necessitating the consideration of coexistence between different layers of networks. Low-altitude coverage must at least address coexistence between low-altitude and ground networks, as well as between low-altitude networks (e.g., drones) and mid-to-high altitude networks (e.g., commercial aircraft). Furthermore, the introduction of RIS also brings about unique network coexistence issues. Existing RIS typically exhibit broadband characteristics, which not only tune signals within the target spectrum but also affect non-target signals, leading to significant network coexistence challenges[52][53]. References[52][53][54][55][56] propose various effective solutions to address these issues.

The ubiquitous deployment of RIS, through dynamic electromagnetic wave control, can effectively manage interference, thereby better supporting network coexistence. The dynamic electromagnetic wave control enabled by widespread RIS deployment can also effectively regulate interference, facilitating the coexistence of UAV networks.

I. RIS-Based UAV ISAC Networks: High-Frequency Bands (mmWave)

Millimeter wave (mmWave) technology for UAV has garnered significant attention, with numerous research findings published. This section will review typical findings and discuss the topic of RIS-based communications and sensing for UAV in the mmWave bands.

The survey in[57] provided an overview of related works in UAV communications and technology integration. It explored millimeter wave (mmWave) beamforming enabled UAV communications, addressing both technical potential and challenges, as well as relevant mmWave antenna structures and channel modelling. Additionally, technologies and solutions for UAV-connected mmWave cellular networks and mmWave-UAV ad hoc networks are reviewed.

UAV operating in the mmWave spectrum represent an exciting frontier in wireless communication technology. However, UAV mmWave communication presents several significant challenges that need to be addressed for successful implementation and reliable operation[58][59].

Notably, in the future development of wireless networks, the introduction of RIS technology offers an innovative solution to the problem of high-frequency path loss. RIS, with its remarkable advantages of low cost, low power consumption, and low complexity, exhibits immense potential in fully utilizing the bandwidth of mmWave and terahertz bands. Through the application of RIS, we are likely to unlock the infinite possibilities of high-frequency spectral resources, inaugurating a new paradigm in high-frequency resource utilization.

1) Free Space Propagation Model—Friis Formula

This model assumes that radio waves propagate in a vacuum, free from obstacles and interference, with received power decreasing exponentially with distance. This attenuation can be described by the Friis formula[60]. The Friis formula, also known as the Friis Free Space Formula or Friis Transmission Equation, is the fundamental equation describing the free space propagation model. Proposed by Danish-American radio engineer Harald T. Friis in 1946, it closely links transmission power, antenna gain, distance, wavelength, and received power, making it one of the most important equations in antenna theory.

Friis formula shows that the relationship between frequency and free-space fading is based on the assumption of a simplified isotropic antenna effective area A_{er}, which is directly related to the type of antenna. However, the definition of path loss clearly states that "path loss is a measure of the reduction in signal strength due to distance and obstacles during the propagation of radio waves," meaning it should fundamentally be concerned only with the propagation of radio waves and not directly with the specific factors of the transmitting and receiving antennas. In other words, ideally, we consider only the effects of the propagation path of the electromagnetic wave, treating the transmitting and receiving antennas as independent of the influence of the propagation path. In other words, when considering electromagnetic wave propagation alone without accounting for the characteristics of the transmitting and receiving antennas, free-space attenuation is independent of frequency. However, the free-space path loss model defined by the Friis formula explicitly considers the characteristics of the receiving antenna.

2) RIS Paving the Way for a New Paradigm in High-Frequency Resource Utilization

In practical engineering, the three core constraints in antenna design are cost, power consumption, and complexity, while also considering the physical space and load-bearing capacity of the deployment environment. As the frequency increases, a notable trend is that the ratio of the antenna's effective aperture to its physical size tends to decrease, meaning that to maintain the same effective aperture, the physical size of the antenna must be enlarged as the frequency increases. Additionally, due to current technological limitations, the manufacturing cost and complexity of individual antenna elements in high-frequency bands also increase. These two factors combined make it more challenging to achieve equivalent performance in high-frequency antennas, leading to higher costs and more complex system designs.

However, the growing attention to meta-surface technologies, particularly RIS, offers an innovative solution to this problem with its characteristics of low cost, low power consumption, low complexity, lightweight design, and ease of deployment. By introducing RIS, a new material and technology, novel phased array antennas based on intelligent meta-surfaces have emerged, offering a promising approach to achieving larger effective apertures.

In fact, prototype mmWave and Sub-THz phased array antennas based on RIS have already been successfully developed and empirically validated, with their outstanding performance fully demonstrating the feasibility and potential of this technological pathway. Looking ahead, in the deployment of 5G-A and 6G networks, considering the multiple challenges of cost, power consumption, complexity, and deployment difficulty, RIS-based novel phased array antennas are poised to be game-changers, enabling frequency-independent effective apertures. This could effectively mitigate or even eliminate concerns about path loss in high-frequency bands (particularly mmWave and terahertz bands) under the Friis path loss model. This implies that future wireless networks will be able to fully exploit the rich spectrum resources of high-frequency bands without being hampered by the prejudice of "excessive path loss," thereby ushering in a new paradigm of high-frequency resource utilization.

IV. Standardization

Standardization is crucial for achieving large-scale commercialization of communication technology. Recently, relevant organizations have carried out a series of activities to promote the standardization of UAV communications.

Since the 4G LTE standard phase, UAV connectivity has been one of the focal points in many research efforts within the Third Generation Partnership Project (3GPP)[61][62][63]. For instance, 3GPP Release 14[61] specifies that UAV must maintain continuous connectivity with the cellular network while flying at speeds of up to 300 km/h.

The 3GPP has made significant efforts to ensure that cellular networks can meet the connectivity requirements of UAV in 5G NR[64][65][66], as illustrated in Table II. In 2017, 3GPP approved a study project aimed at enhancing LTE support for UAV, with the primary goal of identifying the key challenges in providing connectivity for UAV using existing LTE networks with down-tilted BS antennas. To further address UAV connectivity, identification, and tracking requirements, 3GPP has recently considered the application of 5G networks in Release 17[66]. Several other standardization bodies and working groups have also dedicated considerable efforts to developing UAV-specific regulations[67], including the International Telecommunication Union Telecommunication Standardization Sector (ITU-T)[68], the European Telecommunications

Standards Institute (ETSI)[69], and the IEEE Drone Working Group (DWG). Additionally, to foster research, design, and innovation in aerial communications, the IEEE Vehicular Technology Society (VTS) established a Drone Ad Hoc Committee, while the IEEE Communications Society (ComSoc) launched an Emerging Technologies Initiative focused on aerial users and networks[70][71]. One of the initiative's target applications is public safety, which involves providing additional cellular coverage through aerial communication, such as during emergency situations, or delivering advanced services to assist first responders. Moreover, two standards working groups, jointly initiated by IEEE ComSoc and IEEE VTS, are focused on developing standards for aerial communications and networks[72]. Regarding the atmospheric duct, a study item "Study on remote interference management for NR" was agreed for 5G Release 16, in the 3GPP TSG RAN #80 meeting. And the work item "Cross Link Interference (CLI) handling and Remote Interference Management (RIM) for NR" is issued by 3GPP. In such study/work item, remote interference management (RIM)a ims to investigate possible techniques for mitigating the impact of remote interference caused by atmospheric duct[73].

Additionally, 5G-A Rel-18 was completed in June 2024, with its ISAC standardization content serving as a foundation for UAV ISAC standardization. The ongoing Rel-19 ISAC channel modeling, once its standardization work is completed, can also serve as a basis for research on UAV ISAC channel modeling.

In the future 6G standardization process, it will be necessary to address not only the individual standardization efforts for UAV communications and RIS, but also the specific standardization work that considers the integration of RIS with UAV communications. At a minimum, scenarios and relevant solutions for RIS-enabled UAV ISAC networks, as discussed in the previous sections, should be considered.

V. RIS-Based UAV Coverage Field Trial

To be added Recently in Chongqing City of China, a field trial was conducted for UAV. The site is a playground in the university campus, surrounded by small hills. The test UAV flew above the ground at the height of 120 m, along a grid that covers the ground below. The BS is located 150 m away from the center of the playground, operating in 2.6 GHz and 4.9 GHz, respectively. Two RIS panels are tested. The one for 2.6 GHz has 32×16 = 512 elements and the other one for 4.9 GHz has 32×32 = 1024 elements. These two panels are located near the center of the playground, lying on the ground with zero degree in elevation angle (refer to **Fig. 4**).

Figure 4. RIS-based UAV coverage field trial

Even though the RIS panels can only be phase tuned in a semi-static fashion, e.g., to cover a fixed area rather than dynamic steering the reflected beams to the flying NAVs, the gains in reference signal received power (RSRP) and signal to interference noise ratio (SINR) are still about 2.5~4 dB, which demonstrates the feasibility of deploying RIS to direct beams towards UAV and improve the strength of desired signal and suppress the interference.

VI. Future Technology Trends

Although the solutions proposed in this paper address UAV signal coverage issues to some extent, several areas still require further research and optimization. The main challenges include:

1) Variability of the Atmospheric Ducting Effect

The atmospheric ducting effect is highly variable and heavily influenced by meteorological conditions, making it difficult to develop a generic propagation model. Researchers need to conduct extensive experiments and data collection to foster a deeper understanding of ducting effects under different conditions and to develop corresponding compensation techniques. Furthermore, flexible approaches to adapt to the changes in ducting effects in real-world applications are necessary to ensure stable signal propagation.

2) Coordinated Optimization of Multi-layer Networks

A major challenge in multi-layer network architecture is to achieve coordinated optimization across different network layers. Given that network nodes at different layers have varying characteristics and capabilities, coordinating resource allocation and interference management can be complex. New cooperative mechanisms and optimization algorithms are needed to facilitate efficient collaboration among the network layers.

3) RIS-based UAV Network Deployments

The issue of UAV signal coverage is a complex and multi-dimensional challenge that requires efforts on multiple fronts. Through research and application of intelligent antenna systems, massive MIMO technology, multi-layer network architecture, atmospheric ducting effect modeling, and security and privacy protection technologies, the overall performance of UAV communication systems can be significantly improved. Future research should strike a good balance between theory and practical engineering, to provide solid theoretical support and practical guidance for the development of UAV communication systems.

VII. Conclusion

Low-altitude coverage presents unique challenges, when compared to ground-level coverage. UAV networks, characterized by high mobility and different service distribution, represent a typical application scenario for ISAC. The dual-layer heterogeneous topology required for UAV networks necessitates continuous three-dimensional coverage, posing the challenge of multi-layer network coexistence. Additionally, the distinct characteristics of UAV channels, such as the predominance of LoS paths, lead to difficulties in controlling cell coverage areas and may result in increased co-channel interference between neighboring cells. The up-tilt configuration required for UAV antennas, in contrast to the down- tilt used in conventional ground coverage, can also exacerbate atmospheric ducting effects, especially in TDD systems, which may lead to cross-link interference over long distances between cells.

To address these issues, Sub-6 GHz frequencies are suitable for supporting small-scale UAV low-altitude coverage through the addition of new BSs. However, for large-scale low-altitude coverage, new mid-band and mmWave frequencies are more appropriate. RIS, with their advantages of low cost, low power consumption, and low complexity, have the potential to serve as a key enabling technology for achieving continuous low-altitude coverage in these frequency bands, making RIS as a fundamental element in future wireless networks. Additionally, a field trial has been conducted to validate the RIS-based low-altitude coverage solution for UAV. The field test results demonstrate that RIS can effectively support UAV low-altitude coverage.

Future research should focus on the emerging challenges of low-altitude UAV coverage and explore RIS-based solutions for continuous coverage in new mid-band and mmWave frequencies. Additionally, efforts should be made to accelerate the commercialization of non-standard RIS-based products in the 5G-A phase and to promote the standardization of RIS for 6G, enabling large-scale deployment of RIS-based solutions.

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Footnotes

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