

RIS-ASSISTED UAV-ENABLED CELL-FREE MASSIVE MIMO SYSTEMS FOR 6G WIRELESS COMMUNICATION

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Abstract

The sixth-generation wireless networks are anticipated to provide ultra-reliable low latency communication, massive connectivity, high spectral efficiency, better energy performance, and seamless service availability in terrestrial, aerial and remote environments. To fulfill these requirements, recent works have been increasingly focused on integrating reconfigurable intelligent surfaces, unmanned aerial vehicles and cell-free massive multiple-input multiple-output architectures. Reconfigurable intelligent surfaces offer programmable control over the wireless propagation environment, unmanned aerial vehicles provide flexible 3D deployment and fast coverage extension, and cell-free massive MIMO improves user-centric service by coordinating distributed access points without rigid cell boundaries. This survey provides a structured overview of RIS-assisted UAV-enabled cell-free massive MIMO systems for 6G wireless communications. It covers enabling technologies, system architectures, channel modeling, UAV trajectory optimization, RIS phase configuration, resource allocation, energy and spectral efficiency, physical layer security, scalability, and practical deployment issues. The study also compares recent approaches based on performance objectives, optimization methods, application domains and implementation constraints. The review shows that the combined use of RIS, UAVs and cell-free massive MIMO can significantly improve coverage, reliability, interference management and energy-aware operation, particularly in scenarios susceptible to blockage or highly mobile or with limited infrastructure. However, imperfect channel state information, RIS hardware impairments, UAV battery constraints, synchronization overhead, high computational complexity, security risks, and lack of mature standardization still hinder the practical deployment. Based on the review of the literature, future research directions include lightweight channel estimation, AI-assisted joint optimization, energy-efficient UAV control, secure RIS configuration, multi-UAV coordination, experimental testbeds, and interoperable protocols. In summary, the RIS-assisted UAV-enabled cell-free massive MIMO is a promising architecture which is still evolving to achieve flexible, intelligent and scalable 6G wireless networks.

I. INTRODUCTION

The sixth generation (6G) wireless communication is expected to make a huge leap from 5G by providing ultra-reliable low-latency communication (URLLC), facilitating massive device connectivity and improving energy and spectral efficiency. These capabilities are required to support applications such as autonomous transportation, extended reality (XR), smart cities, remote healthcare and large-scale Internet of Things (IoT) deployments. 6G networks are also anticipated to support new use cases such as holographic telepresence, E-Health platforms, always-on connectivity in smart environments, large scale robotics, 3D unmanned mobility, augmented reality (AR), virtual reality (VR) and Internet of Everything (IoE). Such applications require near global coverage, data rates approaching 1 Tbps, end-to-end latency below 0.1 ms, and reliability on the order of 99.99999%, far

beyond what current 5G systems can provide. By 2030 the number of connected devices is expected to grow to billions, putting pressure on networks to support very diverse traffic patterns, from high rate video streams to low power sensor messages [1]. The typical cellular architectures based on fixed cell layout and fixed position of base stations are facing clear limits in terms of scalability, interference management, and ability to adapt to fast-changing user distribution and channel conditions. For example, in dense urban areas or sparsely covered rural areas, blockage and path loss may severely degrade the quality of the link [2]. These challenges lead to new techniques at the architectural level as well as at the physical layer to meet 6G targets such as lower energy consumption to enable sustainability goals, and the incorporation of artificial intelligence (AI) for more autonomous network management [1], [3] and AI applications such as used in [229], [231].



Fig. 1. Characteristics of 6G Networks.

A practical way forward is to integrate Reconfigurable Intelligent Surfaces (RIS), Unmanned Aerial Vehicles (UAVs), and Cell-Free Massive MIMO (CF-mMIMO) to build a flexible, software-controlled wireless architecture. RIS are meta-surfaces made of many passive elements that can alter the phase, amplitude or polarization of the incident electromagnetic waves so as to

reconfigure the radio channel [4], [5]. RIS provide a low-cost and energy-efficient approach to mitigate signal attenuation and interference [6], as they do not require power-consuming radio frequency (RF) chains or heavy baseband processing. For more advanced designs, e.g., the Simultaneously Transmitting and Reflecting (STAR) RIS, each element can simultaneously

transmit and reflect signals, which enables the surface to serve users on both sides and better utilize spatial resources [7], [8]. UAVs complement these surfaces by adding three-dimensional mobility, quick deployment, and real-time adjustment to changing propagation conditions. They can act as aerial access points (APs), relays, or flying platforms that carry RIS panels [9]. For instance, UAVs can adjust their position to avoid obstacles and maintain line of sight (LoS) links, extend service to remote or disaster-hit regions, and move to locations that improve channel quality [10], [11]. When fitted with RIS (UAV-RIS), they can reduce the need for high-power RF hardware, which helps extend flight duration and supports flexible mobile operation [12]. CF-mMIMO, in contrast, removes fixed cell borders by coordinating a large number of distributed access points through a central processing unit. It removes the traditional notion of fixed cells by distributing many access points across the coverage area and coordinating them through a central processing unit (CPU), which helps maintain consistent service quality and lowers inter-user

interference [13]. Unlike co-located massive MIMO, CFmMIMO exploits macro-diversity by using many geographically separated APs, each possibly equipped with multiple antennas, that cooperate to serve users through spatial multiplexing over the same time-frequency resources. [14]. When RIS, UAVs, and CF-mMIMO operate together, they offer high flexibility, improved spectral and energy efficiency, and reliable links in both line-of-sight (LoS) and non-line-of-sight (NLoS) conditions, making them strong candidates for future 6G systems [1], [14]. Recent work has shown that the incorporation of RIS into CF-mMIMO can mitigate weak scattering and blockage-induced attenuation, while UAVs introduce mobility that can be leveraged to maintain performance in challenging environments [15], [16]. In particular, UAV-RIS can act as flying reflectors to enhance the downlink rates with optimized power control and precoding schemes, e.g., conjugate beamforming (CB), which can bring substantial performance gains in user-centric networks [16], [17], [18].

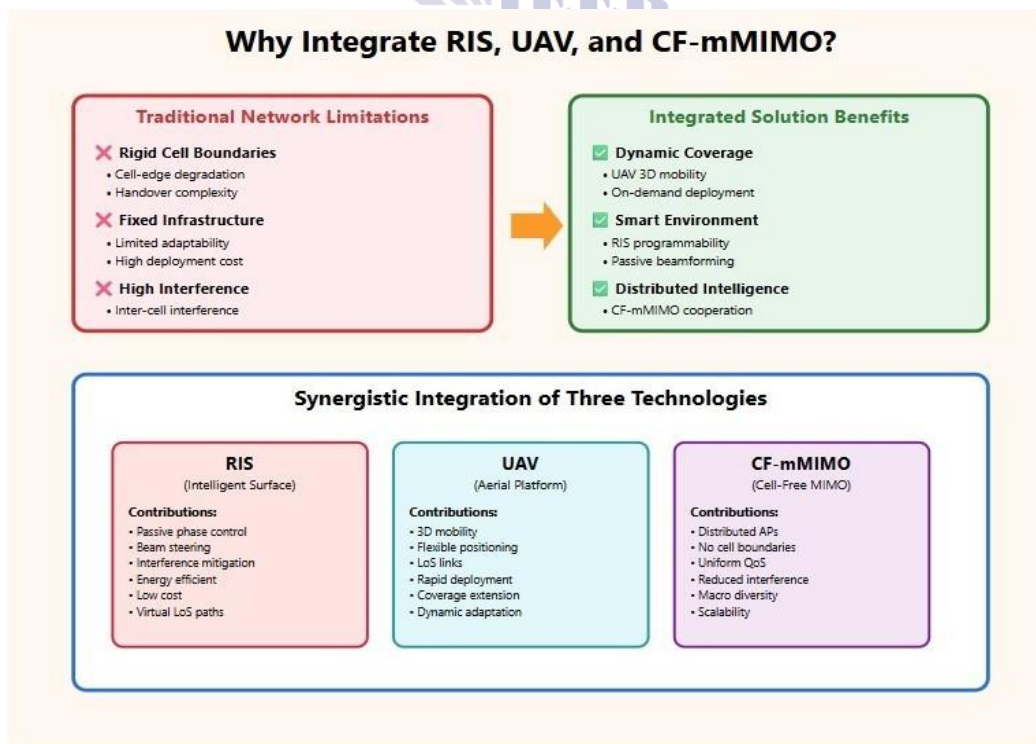


Fig. 2. Integration Necessity of different Technologies.

This hybrid approach is motivated mainly by the limitations of previous network architectures. Traditional cellular systems, in which fixed base stations are used, are impacted by inter-cell interference, which hampers the achievement of 6G performance targets [19]. Cell-free massive MIMO (CF-mMIMO) was proposed as a more user-centric approach, where a large number of distributed APs serve in a cooperative manner, providing a more uniform quality-of-service (QoS) and alleviating the typical cell-edge problems [20]. However, despite the benefits of these technologies, for example in congested areas with obstructions or in cases of high user mobility, environments with severe signal blockers remain challenging to handle [20].

RIS can overcome these difficulties by passively reconfiguring the propagation environment to create virtual LoS links and suppress interference without increasing transmit power [21], [22]. UAVs provide further flexibility due to their capability to change their location and altitude. They can be used as flying APs in CF-mMIMO systems or equipped with RIS panels to steer the signal around blocking objects. This is especially useful in use cases such as surveillance, setting up temporary emergency communications, and rapidly reestablishing coverage after natural disasters. [10], [23]. The integration of passive RIS elements with well-designed UAV movement patterns can enable RIS and UAVs to work together to increase the overall system throughput, while also enabling a more energy-aware operation [24], [18]. This survey aims to provide a clear and structured analysis of this emerging research area, with the following main contributions:

In this paper, we provide a comprehensive study on the application of RISs and UAVs in CF-mMIMO systems, highlighting their complementary role in enhancing coverage, capacity and reliability. This involves, for example, system architectures where RIS elements are tuned for phase shifts, UAV trajectories are designed using alternating optimization methods, and CF-mMIMO applies scalable precoding schemes like zero-forcing (ZF) and maximum ratio combining (MRC) to increase sum rates [25], [26].

We review recent work on RIS-UAV-CFmMIMO designs, including system models, UAV trajectory optimization (e.g., gradient-based methods for placement, manifold optimization for phase design), RIS deployment strategies (fixed versus mobile), channel models (Rayleigh for NLoS and Rician for LoS with UAV links), and cross-layer approaches based on AI for resource allocation and beamforming [1], [27], [28].

We present the main performance metrics in a quantitative manner, with comparisons between RIS-assisted and conventional CF-mMIMO systems, plots based on simulations (e.g., sum-rate versus SNR, energy-efficiency curves), a classification of major research directions (e.g., channel estimation, interference control), and common analysis tools (analytical expressions, Monte Carlo simulations) [29], [30], [31].

We bring attention to open issues such as hardware imperfections (e.g., phase quantization), energy constraints (UAV battery life, RIS power consumption), control signaling overhead (for RIS configuration, and the coordination of UAVs), and physical-layer security threats (e.g., eavesdropping in open-air links). We also discuss the possible future directions including AI-based optimization, operation in THz bands, multi-UAV cooperation, and experimental prototypes for 6G systems that employ RIS and UAVs in CF-mMIMO architectures [32], [6], [9], [33].

Moreover, we consider the interplay of these systems with other 6G technologies, such as next generation multiple access (NGMA), simultaneous wireless information and power transfer (SWIPT), and millimeter wave (mm Wave) links, where RIS-aided UAV-CFmMIMO designs can enable energy harvesting and alleviate the impact of blockages [34], [35]. This survey extends recent progress, such as closed-form expressions for achievable rates and robust designs against imperfect channel state information (CSI), as a reference for researchers and engineers for practical 6G deployment [15], [18].

To make the survey systematic and easy-to-follow, the remaining parts of this paper are organized based on key technical components and performance issues of RIS-assisted UAV-enabled CF-mMIMO systems. First, we survey the enabling

technologies to describe the role of RIS, UAVs and CF-mMIMO in 6G wireless networks. Next, a Materials and Methods section is presented to describe the literature selection process, search scope, inclusion criteria, and classification method used to organize the reviewed studies. The reviewed works are categorized based on system architecture, channel modeling, trajectory optimization, RIS phase design, resource allocation, energy efficiency, spectral efficiency, physical layer security, and emerging 6G applications. We separate the Results and Discussion section in order to compare existing approaches, to identify common performance trends and to highlight the main limitations that still constrain practical deployment. This architecture allows the survey to move beyond a mere descriptive review and offers a more robust foundation for the study of open challenges and future research directions in RIS-assisted UAV-enabled CF-mMIMO networks [1], [14], [25]–[35].

II. BACKGROUND AND ENABLING TECHNOLOGIES

A. Reconfigurable Intelligent Surfaces (RIS)

- Reconfigurable Intelligent Surfaces (RIS) [2] is a new type of programmable meta surface, which is used to shape the wireless channel. An RIS consists of many low-cost, mostly passive elements that can modify the phase, amplitude or polarization of incoming electromagnetic (EM) waves. Each element is individually controlled by a central controller, usually through software-defined links. The surface is then able to respond to changing channel conditions in real time.

- Depending on the construction, RIS panels can function in several modes. In passive mode the elements simply reflect the incoming signals with very low power consumption. It is like a controlled mirror that directs the radio waves towards selected receivers. In active mode small amplifiers are added to provide limited gain and to help compensate for path loss. A more advanced option is the Simultaneous Transmit and Reflect (STAR) RIS, where each element can simultaneously transmit and reflect towards different directions, so the surface can serve users on both sides, not just one side.

- The ability of RIS panels to steer beams, adjust reflections, and tune phase responses allows for the reshaping of the radio environment rather than adapting to it. It is especially useful in solving common wireless problems such as signal blockage, high path loss and multipath fading in dense urban areas or difficult non-line-of-sight (NLoS) scenarios. In a RIS-assisted system, the base station or distributed access points (e.g., in CF-mMIMO) can tune the surface to create virtual line-of-sight (LoS) paths. This amplifies the desired signals, increases spectral efficiency and allows the network to achieve rate targets with lower transmit power.

- In conjunction with Unmanned Aerial Vehicles (UAVs) and Cell-Free Massive MIMO (CF-mMIMO), the panels serve as controllable tools that complement the UAV mobility and the cooperative operation of CF-mMIMO. Deployed on UAVs, RIS panels can be steered in 3D to enhance links to ground users or provide aerial backhaul. This makes it easier for the system to respond to user movement, obstacles in the environment and changing interference patterns.

- For CF-mMIMO systems, where a large number of distributed APs serve all users jointly without the existence of strict cell borders, RIS provides a means to coordinate and shape the signals by redirecting the scattered energy in a controlled manner. The result is better coverage handover across the service area, more uniform quality of service (QoS) and less pilot contamination.

- Energy-aware network design is also possible using RIS technology. Since RIS panels consume very low power and do not need full RF chains, they generate lesser unwanted emissions than the conventional active relays or very large antenna arrays. This makes them suitable for wireless networks that seek to reduce power consumption while maintaining acceptable performance levels [36], [37].

B. UAV-Based Wireless Networks

- Unmanned Aerial Vehicles (UAVs) are gaining more and more significance in the next generation wireless networks, since they can cover the area from the air, be deployed in a short time

period, and change their position according to the channel conditions and user demand. UAVs can change their height, position and trajectory to improve service quality, in contrast with traditional ground base stations that are static, have limited line-of-sight (LoS) links and often perform poorly in difficult terrain. This makes them particularly useful in dense urban environments, post-disaster settings, military communications, and temporary large events where user locations and traffic load change over time.

- UAVs can play several roles other than the traditional aerial base stations in Reconfigurable Intelligent Surface (RIS)-assisted Cell-Free Massive MIMO (CF-mMIMO) systems. First, UAVs can act as aerial access points (APs) to directly provide services to ground users in the presence of good LoS links, and support low-latency and high-rate communications. Secondly, they can serve as aerial relays for forwarding signals between users and distributed APs when direct paths are blocked by obstacles such as high-rise buildings, dense vegetation or hills. Third, UAVs can be equipped with RIS panels to become flying reflectors or STARRIS platforms for tuning their reflection and transmission properties to improve beamforming, mitigate interference, and even out coverage especially when fixed RIS deployment is hard or too expensive. Authors in [227] also consider UAV-aided backhauls in THz-enabled

- At the same time, several major barriers to large scale deployment of UAV-based wireless systems. The flight time of UAVs is constrained by the battery capacity and also the payload capacity is limited, making it difficult to carry large RIS panels or powerful processing hardware. Airspace regulations and safety rules, and the need to manage interference between multiple UAVs, add further complexity. They also demand secure control links, immunity to jamming and robust signaling protocols to ensure their operation in shared or contested airspace.

- UAV-assisted RIS-CF-mMIMO networks are a new trend in the design of 6G systems that integrate mobility and channel programmability to provide efficient, resilient and energy-aware

hybrid heterogeneous networks, where aerial platforms can provide high-capacity links when terrestrial backhauls are weak, congested or unavailable.

- The integration of UAVs, RIS and CF-mMIMO improves the reliability, flexibility and spectral efficiency of the network. UAV-mounted RIS panels can create alternative paths for electromagnetic waves in heavily multi-path and often blocked city environments to preserve link quality and maintain connections. UAVs can provide connectivity without the need for permanent ground infrastructure by quickly establishing temporary backhaul links in remote or hard to reach locations. Their mobility and controllability also allow for updating of flight paths and RIS configurations commensurate to user movement, traffic patterns and energy budgets.

- UAV-assisted RIS-CF-mMIMO systems also help improve both spectral and energy efficiency. By choosing suitable positions and using coordinated beamforming, UAVs can cut down propagation losses, shrink interference regions, and reduce the required transmit power. UAVs can also carry sensing equipment and run learning-based algorithms, which is useful for tasks such as emergency response, surveillance, environmental monitoring, and support for smart city services.

wireless coverage in general. They can enable a wide variety of applications such as autonomous platforms, massive IoT deployments, disaster relief, and beyond-5G high-rate broadband services [38], [39] when properly designed and optimized.

C. Cell-Free Massive MIMO (CF-mMIMO)

- Cell-Free Massive MIMO (CF-mMIMO) is a novel network architecture that abolishes the traditional cellular layout with separate base stations. Instead of partitioning the area into static cells, multiple access points (APs) with one or more antennas are distributed over the coverage area and connected to a central processing unit (CPU) over high-capacity fronthaul links. Contrary to the conventional cellular systems

where each user is associated with one base station in a fixed cell, CF-mMIMO removes the strict cell boundaries. Several nearby APs serve each user at the same time in a cooperative, user-focused way, which helps to control interference and maintain more uniform service quality across the whole network.

- This cell-free approach helps address several well-known issues found in traditional cellular networks:

- **No cell-edge degradation:** Users located at the edge of what would be a cell in a traditional system no longer experience weak signals or strong interference from neighboring cells. Instead, each user is served by multiple nearby APs to ensure uniform performance over the coverage area.

- **Near far fairness:** In traditional systems, the users near the base station generally have much

better signal conditions than the users at the cell edge. In CF-mMIMO, power control and precoding are jointly performed among all APs such that the signal levels are equalized, leading to more uniform performance among the near and far users.

- **Inter-user interference reduction:** APs transmit and receive in a coordinated way, and are able to adapt their signals so that desired components add up constructively, and unwanted components largely cancel each other out. This coordination enables the system to maintain many users simultaneously, even in crowded scenarios.

- In CF-mMIMO, access points are spread throughout the coverage area and placed much closer to users, often only a few tens of meters away. The shorter link distance improves channel conditions,

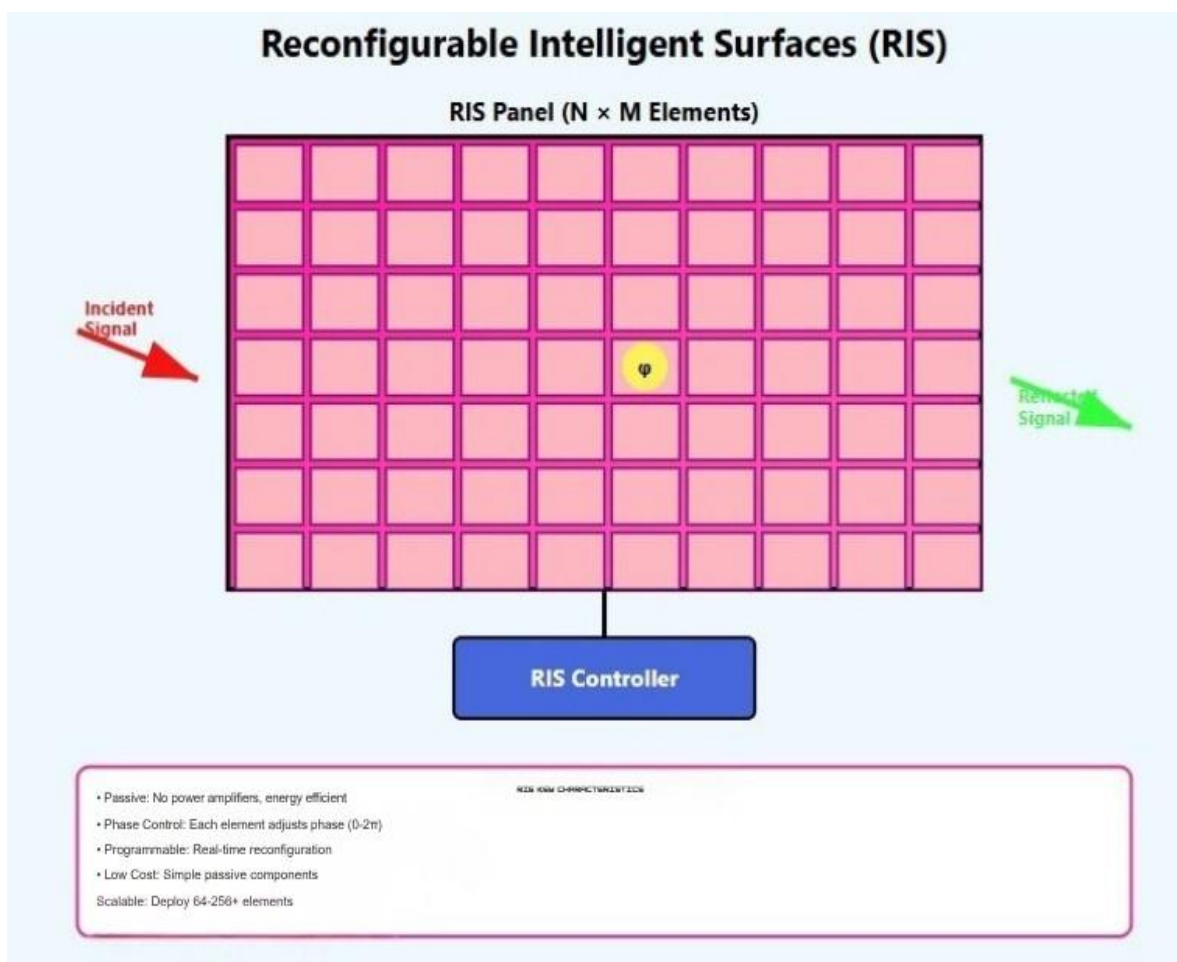


Fig. 3. Reconfigurable Intelligent Surface (RIS).

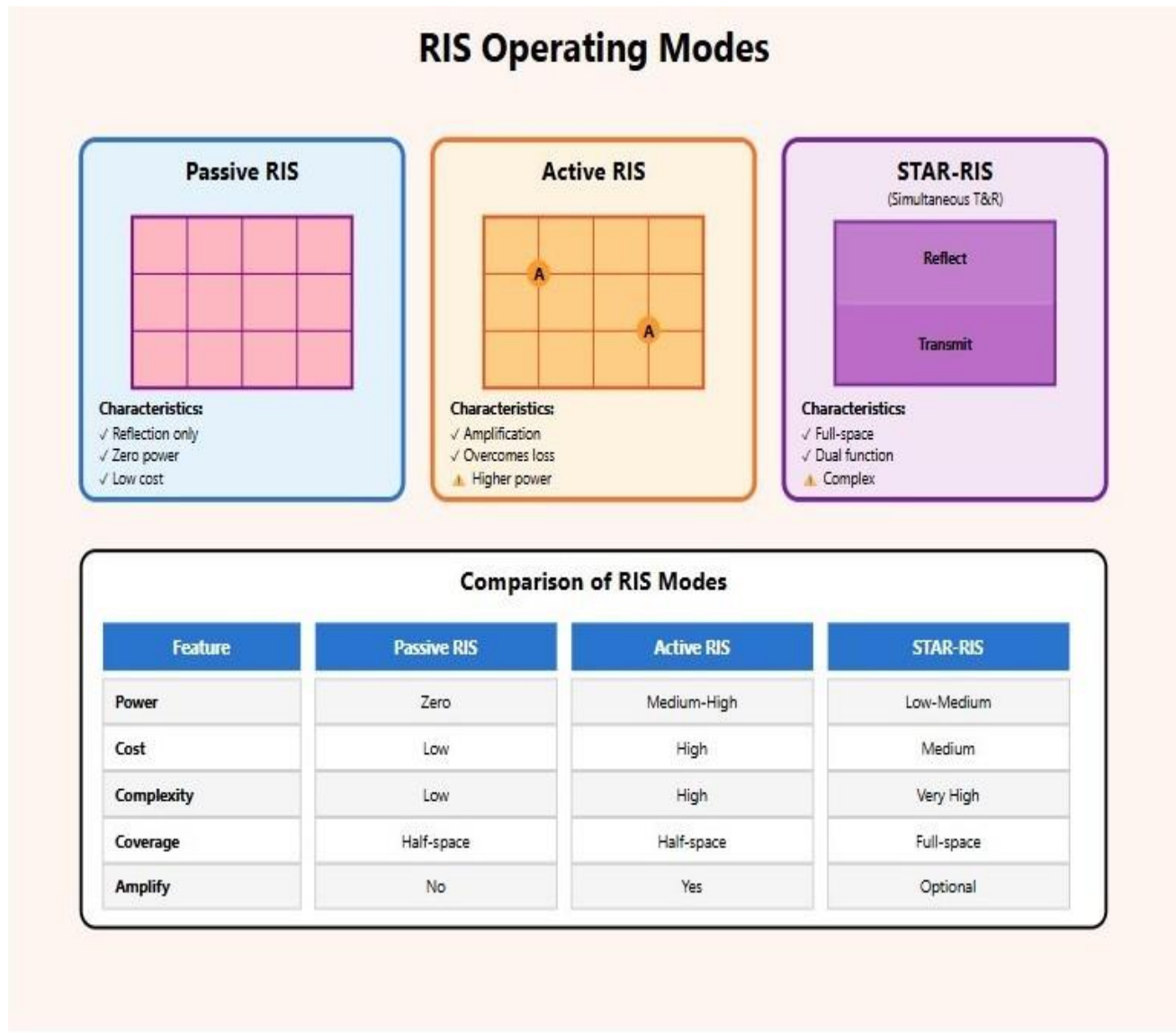


Fig. 4. RIS Operating Modes.

reduces path loss and increases the signal-to-noise ratio (SNR). Combined with macro-diversity, where users receive signals over several independent paths, this leads to clear gains in both spectral efficiency and energy efficiency.

➤ **Higher SE:** The channel varies less, spatial multiplexing is used more efficiently and

interference is better controlled so the system can carry more bits per Hz.

➤ **Lower power consumption:** This leads to lower transmit power as the links are stronger and APs work together in serving the users, and the target data rates can be satisfied. This behavior is consistent with an energy-aware 6G operation.

Roles of UAVs in RIS-Assisted CF-mMIMO Systems



Fig. 5. Role of UAVs in RIS-Assisted CF-mMIMO Systems.

One of the main benefits of CF-mMIMO is its good performance in terms of the number of users. In ultra dense urban hot spots, massive IoT deployments or large industrial sites, more APs can be added without network redesign, frequency plan change or complicated handover procedures. The system adapts by forming dynamic virtual cells where each user is served by a group of proximate APs that depends on the user location, mobility and traffic demands. This makes CF-mMIMO suitable for important 6G service categories:

- **Massive machine-type communications (mMTC):** Supporting very large numbers of IoT sensors with low-power, wide-area connectivity.
- **Ultra-reliable low-latency communication (URLLC):** Providing sub-millisecond latency and very high reliability for applications such as autonomous driving, remote surgery, and industrial control.
- **Enhanced mobile broadband (eMBB):** Offering multi-Gbps data rates for AR/VR,

holographic telepresence, and 8K video services in crowded environments.

Signal processing in CF-mMIMO combines cooperation among APs with centralized processing at the CPU:

➤ **Downlink:** The CPU calculates precoding vectors (such as conjugate beamforming, zero-forcing, or regularized zero-forcing) using the channel state information (CSI) gathered from all the APs. Then, these vectors are forwarded to the APs which transmit in a coordinated way such that the signals are summed at the intended users and the interference at the others is reduced.

➤ **Uplink:** The APs relayed received pilot and data signals to the CPU. The CPU combines the users' signals using combining schemes such as maximum-ratio (MR) or minimum mean square error (MMSE) combining to detect the users' signals.

➤ **Channel estimation:** Uplink pilot signals sent from users are received at multiple APs. The

CPU fuses these observations to create a comprehensive description of the channel that allows for accurate beamforming even when users are moving.

- **Fronthaul and backhaul flexibility:** In theory, CF-mMIMO often assumes ideal fronthaul with unlimited capacity, but in practice, real networks have links with finite data rates, and may require quantization, compression, or only partial cooperation between APs. Methods such as over-the-air signaling, distributed processing and AP clustering reduce the fronthaul load while retaining most of the performance benefits, which makes it possible to deploy CF-mMIMO using existing fiber or wireless backhaul solutions.

- **Integration with RIS and UAVs:** Adding RIS and UAVs makes CF-mMIMO much more flexible and better suited to 6G use cases:

- **With RIS:** Reconfigurable surfaces can act as virtual APs, passively reflecting and focusing signals from physical APs to users in blocked or shadowed regions. This allows for smoothing coverage, for increasing the strength of connections in NLoS conditions, and for some control on the way radio waves propagate in the environment.

- **With UAVs:** CF-mMIMO is accessible in 3D space with aerial APs or UAVs with RIS panels, with on-demand coverage in disaster areas, over the sea or for temporary events. They can fill coverage gaps, bounce signals over longer distances and move to positions that better serve active users.

- **Combined RIS-UAV CF-mMIMO:** In this case, a UAV with STAR-RIS is able to hover over a cluster of users, reflect communication signals to the ground terminals and transmit sensing signals for ISAC tasks. In this setting, UAVs and ground APs form a single network, which can adapt its operation to the user demand and the changing channel conditions.

- Standardization and real-world deployment:

- 3GPP is examining CF-mMIMO concepts in Release 19 and later under distributed MIMO and non-terrestrial network (NTN) studies.

- AI and machine learning are becoming increasingly important in CF-mMIMO systems:

- **Predictive resource allocation:** Learning-based models can anticipate traffic changes and assist in deciding when and where APs or UAVs should be activated, deactivated, or repositioned.

- **Adaptive precoding:** Deep neural networks can learn practical beamforming rules that run in real time, easing the computation load at the CPU compared with solving complex optimization problems at every update.

- **Anomaly detection:** AI methods can monitor the network for unusual patterns, such as unexpected interference, hardware faults, or potential security events.

- CF-mMIMO security also benefits from its distributed structure:

- **Physical layer security (PLS):** Multiple APs can work together to send artificial noise toward suspected eavesdroppers while keeping the information signal clear for the intended users.

- **Resilience to attacks:** There is no single point whose failure would bring down the whole system; if one AP is compromised or goes offline, other APs can continue serving the users.

- **Secure fronthaul:** Encryption and authentication on the links between APs and the CPU help protect user data and control messages from interception or tampering.

- Energy-efficient and green design: In addition to reducing the transmit power, CF-mMIMO can reduce the overall energy consumption by powering down inactive APs, providing AP sites with renewable energy sources (such as solar panels or small wind turbines), and applying scheduling policies that consider the power consumption. In dense deployments passive cooling and low power radio hardware can also further reduce energy use and help minimize the network's carbon footprint.

- Field trials by industry vendors and research groups (for example, Ericsson, Nokia, and academic testbeds) have reported spectral efficiency gains on the order of 5-10 times compared with 5G small-cell setups in both indoor and outdoor scenarios.

- Integration with Open RAN enables CF-mMIMO to use disaggregated, vendor-neutral hardware, which supports flexible and cost-effective deployment strategies.
- Future evolution:
 - Terahertz CF-mMIMO: Use very high carrier frequencies to support Tbps data rates, with RIS helping to counteract the strong path loss at these bands.
 - Quantum-assisted CF-mMIMO: Explore the use of quantum techniques, such as entanglement-based key distribution, to enhance security between APs.
 - Space air ground integration: Extend CFmMIMO concepts to include LEO satellites, high-altitude platforms (HAPS), and UAV groups, aiming for wider-area coverage through a combined space, aerial, and ground network.

In this Review, we use CF-mMIMO as the central network architecture for 6G systems. Together with RIS that can shape the radio environment and UAVs that provide 3D mobility, the result is a flexible distributed network that can support service continuity in dense urban areas, remote regions and emergency scenarios alike. The main goal is to provide high data rates, low latency and energy-aware operation under a wide range of scenarios, outperforming traditional cell-based massive MIMO systems [40], [2]. Recent studies on mmWave and THz-enabled aerial and terrestrial heterogeneous networks show that high frequency 6G communication can support very high data rates, however, its coverage performance is severely affected by blockage, propagation loss, aerial node placement, and LoS/NLoS conditions [226].

III. DESIGN CHALLENGES

The synergy of Reconfigurable Intelligent Surfaces (RIS), Unmanned Aerial Vehicles (UAVs), and Cell-Free Massive MIMO (CF-mMIMO) is considered a promising technology for future 6G wireless systems, which offers the benefits of improved spectral efficiency, energy efficiency, ultra-reliable low latency communication and coverage extension over large areas.

Through utilizing the programmable response of RIS, the 3D mobility of UAVs and the user-centric

structure of CF-mMIMO, these systems can adapt to highly different propagation conditions and accommodate a large number of devices while maintaining high quality of service. At the same time, there are several important design problems that remain open at the theory and implementation levels. The limitations of RIS panels are non-ideal reflection behavior, power consumption of control circuits, and difficulties in scaling to very large sizes on the hardware side, whereas UAVs are limited by payload, flight time, and sensitivity to harsh weather. From the signal processing perspective, joint optimization of UAV trajectories, RIS phase shifts and CF-mMIMO beamforming poses high-dimensional problems that are hard to solve in real-time. Another important issue is the energy use, as UAVs are expected to be light and battery-powered and RIS

elements are expected to work with very low power while providing useful gains.

Security and privacy also deserve special attention in RIS UAV CF-mMIMO setups, as open-air links are vulnerable to eavesdropping, jamming, and spoofing. In addition, reliable UAV-assisted communication also relies on reliable positioning information, since GNSS spoofing [228] can mislead UAV localization, disrupt the trajectory control, and degrade the RIS beam alignment accuracy in the dynamic aerial network [220]. In summary, these challenges indicate that the RIS- and UAV-assisted CF-mMIMO systems are practically deployable for 6G only when the hardware design, optimization algorithms, energy-aware resource allocation, and physical-layer security are further improved.

A. Hardware and Implementation Constraints

In practice, hardware limitations affect the RIS panels in substantially different ways than the idealized models typically used in analysis. Phase shifts are typically quantized with low resolution (e.g., 1-3 bits in many prototypes), which may incur quantization losses of about 5-15% of beamforming gain. Reflection and transmission coefficients are also not perfect, as real materials introduce amplitude loss through absorption, dielectric losses and frequency dependent

behavior, which becomes more prominent at mm-Wave and terahertz bands. Furthermore, practical issues such as element misalignment, non-uniform surfaces, coupling between closely spaced unit cells and thermal expansion under temperature variation can cause distortion of the designed response. These combined effects limit the accuracy of beamforming, distort the shaped wavefront, increase the sidelobe levels, and degrade the overall performance. This results in

the gaps of 20%-40% between the simulated ideal gains and the measured results in spectral efficiency, coverage, and interference control. Large RIS panels with hundreds or thousands of elements also increase the complexity of the control and calibration, the power consumption in the control circuits, and mechanical problems, such as rigidity, weight distribution, and sensitivity to wind when installed on moving platforms.

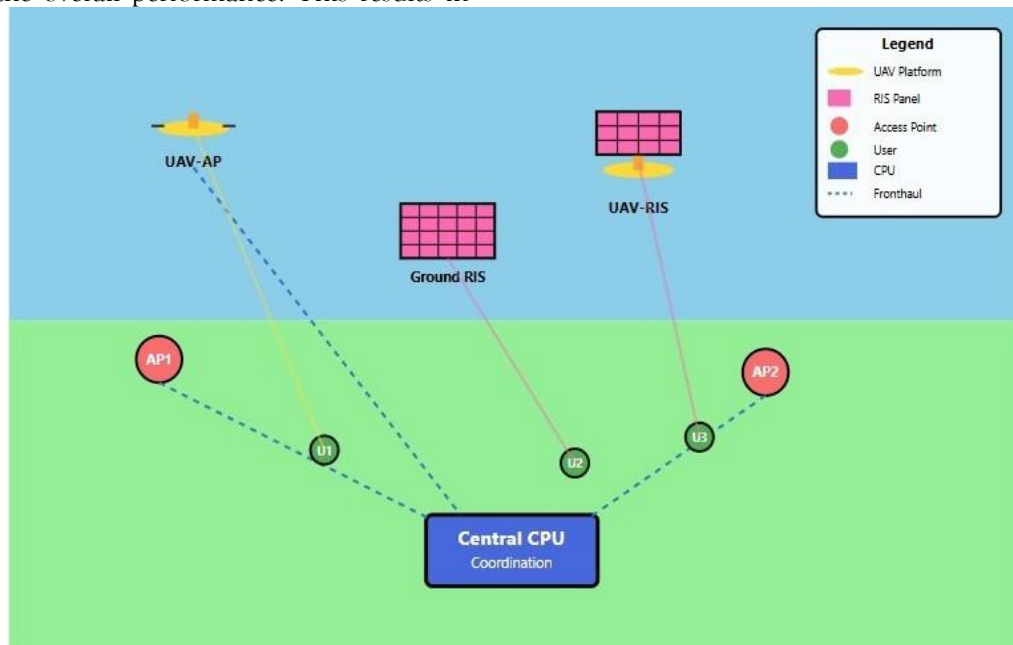


Fig. 6. Example Scenario of RIS-assisted UAV-enabled communication.

UAV platforms have their own size, weight and power (SWAP) constraints. These factors limit the size of a RIS panel that can be carried, the amount of processing hardware that can be installed on board and the battery capacity that can be used. Typical small to medium size UAVs with payloads of about 1-5 kg can only support RIS panels of limited area (e.g. 0.5-2 m² at sub-6 GHz or mm Wave) which imposes trade-offs between the link gain, flying time, stability and reliability. A large RIS surface can add drag, shorten maximum flight time (sometimes to less than 20 minutes when loaded), and reduce maneuverability in turbulent air. Mechanical vibrations may also result in phase drift and navigation errors in GPS-denied environments, and electromagnetic interference (EMI) from motors can affect the RIS alignment and channel coherence.

Another major challenge is the accurate and timely acquisition of channel state information (CSI) under highly dynamic conditions. In UAV-assisted links, the topology may change fast, the Doppler shifts may reach several kHz for high speeds, the line-of-sight (LoS) and non-LoS (NLoS) conditions may switch, and cascaded channels such as AP → RIS → UAV → UE need to be managed. Direct sounding of each link is difficult to apply since RIS elements are passive and do not perform baseband processing or transmit pilots. This leads to the necessity of resorting to indirect or cooperative estimation techniques, e.g., pilot reflection strategies, compressed sensing with sparse recovery, machine learning-based channel prediction (e.g., recurrent or graph-based models), or over-the-air tuning procedures. However, these methods may lead to additional pilot overhead,

latency and processing load at the CPU or edge nodes. Mobility and estimation delay will cause the CSI to be inaccurate or outdated, degrading the quality of precoding, reducing the effectiveness of interference cancellation, and possibly causing coverage holes in CF-mMIMO operation.

It's also not trivial to synchronize the different parts of the system. Coherent joint transmission requires time and phase alignment between multiple UAVs, ground RIS panels, distributed CF-mMIMO APs, and the central CPU. Destructive interference, beam misalignment, pilot contamination, reduced spectral efficiency, and higher error rates can result from small timing errors on the order of nanoseconds or small phase

offsets, particularly when coherent combining is used. Tight alignment typically relies on accurate clock distribution (e.g. GPS-disciplined oscillators or time-sensitive networking techniques such as White Rabbit), low-latency fronthaul, over-the-air calibration signals, and algorithms to compensate for propagation delays and phase changes induced by Doppler. These features increase the protocol complexity, energy consumption and system design.

Real world deployment needs also to take into account other constraints than pure communication performance. UAV operation has to follow rules of aviation for altitude limits, no-fly zones and BVLOS



Fig. 7. Key Design Challenges in RIS-UAV Systems.

missions. The system must be able to operate reliably in various weather conditions (rain, snow, strong winds, high and low temperatures) and

must be electromagnetically compatible with existing radio services. The manufacturing of integrated UAV-RIS platforms at a low cost is still

an open problem. Dependable operation requires solving issues such as heat dissipation for onboard electronics, antenna layout without damaging aerodynamics, and failsafe responses to motor or panel faults, among others, which add further design work.

Overall, the hardware and implementation aspects suggest that future RIS-assisted UAV-enabled CF-mMIMO systems should have improved physical designs (e.g., flexible RIS substrates, low-Swap UAV frames, and energy-harvesting circuits), improved CSI acquisition strategies (e.g., AI-assisted schemes and low-overhead reflective pilots), scalable synchronization approaches (e.g., distributed clocking and over-the-air alignment), and system architectures that explicitly consider the actual deployment conditions. Translating promising theoretical results into practical 6G deployments that can operate reliably in changing and challenging environments will depend on the input from multiple fields including materials science, aerospace engineering, signal processing, and automation.

B. Energy Efficiency and Power Consumption

The primary limitation on UAVs is the capacity of their onboard batteries, which generally allow about 20–60 minutes of flight time depending on the payload, weather, type of mission and aerodynamic conditions. This limitation prevents continuous operation, particularly in situations that require long-duration hovering, large area patrol patterns, or extended availability in emergency response. In most cases, propulsion dominates the total energy consumption, typically by one or two orders of magnitude over the communication and control load. Propulsion energy is tightly coupled to speed and maneuvering effort, so even small inefficiencies in the flight path, such as unnecessary acceleration or suboptimal altitude change, can reduce flight time and break service, requiring frequent landings or handovers of service between UAVs.

RIS panels require little energy for reflection or transmission, but are not completely passive. The tuning phase states, reception of control commands, and the maintenance of

synchronization and switching elements (e.g. PIN diodes, varactors or MEMS structures) come with a non-zero power overhead. This overhead increases with the size of the panels, particularly for STAR-RIS units with thousands of elements that are refreshed frequently. Active RIS designs have been proposed to overcome severe path loss or double fading, but they require amplifiers that add thermal noise and nonlinearities, and they consume extra electrical power. The installation of RIS panels on UAVs adds additional constraints on the mass of the panel, onboard computation for phase updates, communication modules for fronthaul links and stabilization systems. Power density and thermal management are important concerns, as the onboard battery has to support propulsion, signal processing and RIS operation at the same time and has to stay within strict weight limits.

Thus, energy consumption should be jointly optimized for UAV trajectory design, RIS configuration, CF-mMIMO beamforming, user scheduling and fronthaul operation. The goal is not only to improve the spectral efficiency but also to maintain energy efficiency at an acceptable level, increase UAV endurance, and meet latency and reliability requirements. Hence it is a multi-objective design problem with a non-convex structure and time-varying constraints due to mobility of users, varying traffic demand and radio propagation conditions. Conventional approaches such as fixed hovering over demand hot spots or maximizing data rate without considering power tend to drain batteries quickly, while energy-aware approaches need to trade-off between immediate throughput and long-term operational continuity. Communication load, flight mechanics and energy resources are tightly coupled, hence adaptive and predictive control schemes are required. Approaches such as successive convex approximation (SCA), deep reinforcement learning (DRL), and model predictive control (MPC) can be used to find energy-conscious flight paths by preventing quick acceleration, selecting altitudes with beneficial aerodynamic characteristics, and hovering only when necessary. The RIS overhead can be lowered by compressed phase updates, event-driven reconfiguration, or

learning-based prediction of phase settings. Forecasting tools may be used to estimate future energy consumption and support battery planning, energy harvesting (from solar cells, RF exposure or small-scale wind sources) and coordinated swarm operation where tasks shift from low-battery UAVs to recently charged units. Possible solutions to extend the operational time include hybrid power systems with high density batteries and supercapacitors for peak loads, photovoltaic layers on RIS surfaces or ground based wireless power transfer, which would require a careful management of heat and electrical components.

Further considerations are introduced by CF-mMIMO, since distributed processing can ease the CPU load but with the potential to increase the fronthaul energy consumption for sharing the CSI, precoding matrices, and payload data. System-level energy savings can be obtained by leveraging approaches such as over-the-air computation (Air Comp), quantized fronthaul, and scheduling idle APs into low-power modes when UAV coverage is available. In ISAC configurations the same waveform can be used for sensing and communication which removes the requirement for dedicated radar power. The digital-twin simulations can predict the energy consumption of the system considering realistic wind conditions, user distribution and possible signal-blocking obstacles. Addressing energy and power constraints is vital for RIS-assisted UAV-enabled CF-mMIMO systems to move beyond small-scale trials and to be adopted in wide-area deployments. Without coordinated design and better hardware these networks are unlikely to provide near-continuous coverage, and are likely to remain limited to short-term missions. Future developments will depend on the use of lighter and more efficient power units, low-consumption RIS circuits, AI-based energy and power management strategies, the use of renewable sources, and clear indicators to compare energy performance [232][233][234]. These developments make it possible for 6G networks to support longer UAV operation, to operate RIS panels with minimal overhead, and to serve many users with

CF-mMIMO while reducing the overall environmental footprint.

C. Mobility and Trajectory Optimization

The 3D UAV motion plays a pivotal role in the performance of RIS-assisted CF-mMIMO systems. The radio channel is time-varying and it depends on the UAV position, speed, acceleration and orientation in space. This mobility allows coverage to be provided where and when needed, and to set up flexible LoS links. However, it also introduces several difficulties: strong Doppler shifts (which can be several kHz at high speeds), fast channel aging, beam misalignment during turns or altitude changes, and frequent changes in the network topology as UAVs move between user groups or navigate around obstacles. These factors can degrade link quality and affect the accuracy of joint precoding and interference control in CF-mMIMO, especially, when the relative motion is rapid, e.g. in dense urban streets, along high-speed transport routes, in vehicular networks, or in low-altitude air corridors.

Joint optimization of UAV trajectory and RIS phase shift, CF-mMIMO beamforming, user association, and power control simultaneously results in a large-scale optimization problem with multiple performance goals. The unknowns are UAV position in time, the reflection or transmission pattern of RIS, and the precoding vectors at many APs. The constraints are the unit-modulus RIS phases, the propulsion power limits, the collision avoidance and the aviation rules. The objectives of guaranteeing minimum user rates, providing continuous coverage, lowering the total energy consumption and preserving the sensing quality for ISAC are often conflicting. Classical approaches, e.g., successive convex approximation, semidefinite relaxation, or alternating optimization, may fail to meet real-time requirements and scale poorly with the number of UAVs, RIS elements, or APs.

One of the most important trade-offs in the trajectory planning is the trade-off between the covered area and energy consumption. In order to closely follow a moving group of users, it is often necessary to hover for a long time, change position and update the RIS repeatedly, which increases

the propulsion power and reduces the flight time. On the other hand, energy-saving paths that depend on steady cruising or reduced maneuvering may leave some users with weaker links or reduced interference control. The payload

size also matters. Larger STARRIS panels can produce a higher reflection gain, but also increase the drag and weight, which can significantly increase the propulsion energy and reduce the available flight time.

methods are getting noticed: deep reinforcement

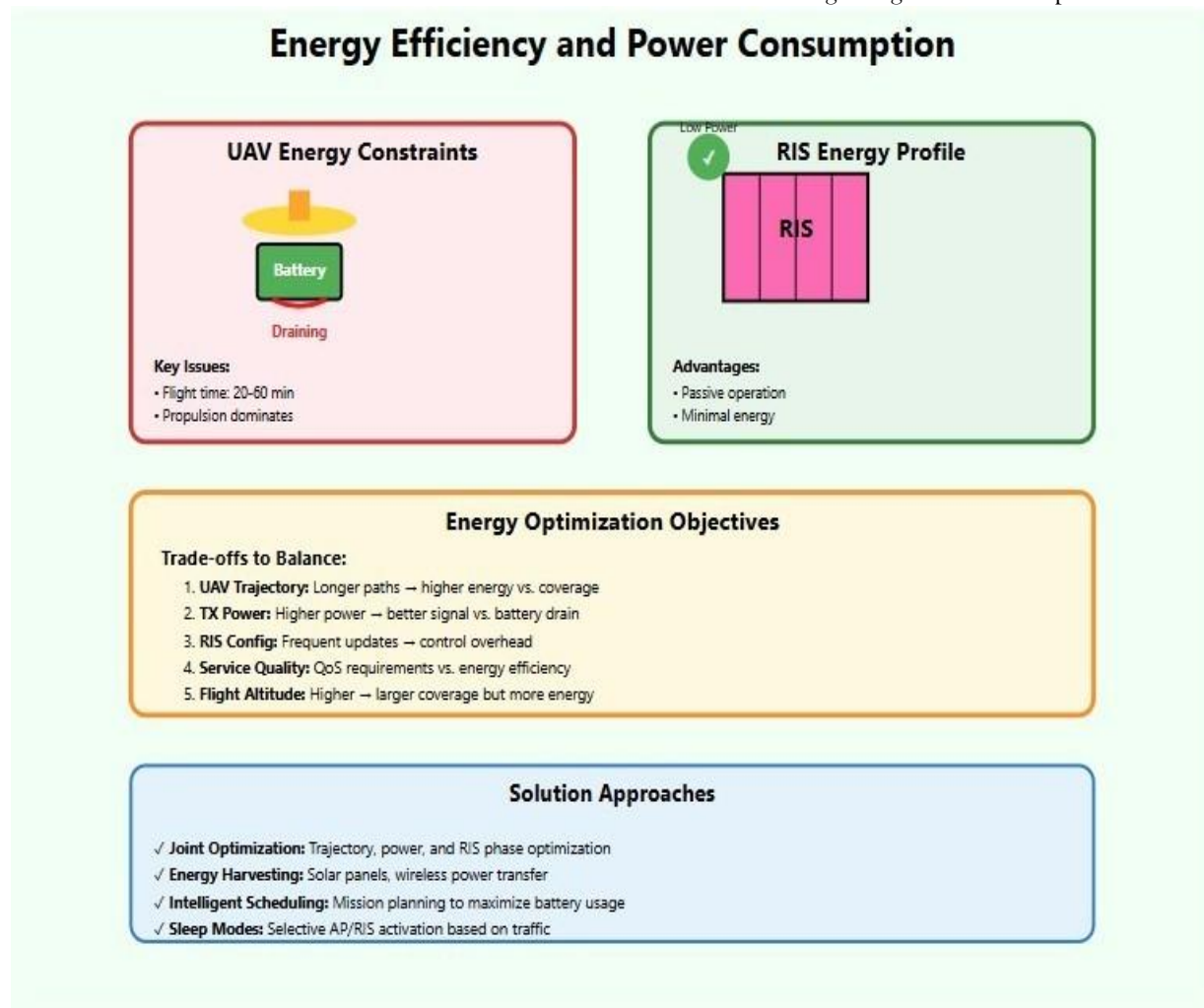


Fig. 8. Energy Efficiency and Power Consumption.

In addition, the uncertain user mobility, unpredictable blockage, and wind disturbances make real-time trajectory control more challenging. It is usually not possible to run complicated optimization routines directly on UAV hardware. Predictive models based on digital twins, stochastic geometry or graph-based learning can predict future channel and traffic conditions but require fast and reliable inference at the edge. Approaches that merge learning and classical

learning (DRL) or multi-agent DRL can learn long-term motion policies for single UAVs or swarms, while model predictive control (MPC) offers short-horizon updates that guarantee stability and feasibility. Distributed optimization techniques such as local updates by over-the-air aggregation can reduce the fronthaul dependency and enhance the scalability.

The performance can be increased by cooperation of several UAVs and groups of RIS elements.

UAV swarms can offer coverage distribution, sharing of sensed information, and Doppler compensation through coordinated combining. RIS elements subarrays common phase behavior reduces the control overhead and synchronization burden. Predictive RIS control can be scheduled according to the planned UAV trajectories to compensate for the expected Doppler shifts and phase offsets in advance. In the areas with unreliable positioning (e.g., GPS-denied areas), the sensing information from ISAC modules can help the UAV to localize itself, and thus enable more accurate motion control. These approaches still require light-weight algorithms, low-overhead

update procedures, tight synchronization and well-defined signaling schemes.

Future efforts may include solar harvesting or laser charging UAV platforms, high-fidelity digital twins for pre-deployment trajectory planning, quantum inspired optimization methods to tackle challenging design spaces and secure swarm coordination based on state-of-the-art cryptographic tools to secure UAV paths against tampering. For the reliable operation of the RIS-assisted UAV-enabled CFmMIMO systems in the highly dynamic and diverse 6G scenarios, a unified mobility management framework over communication, control, sensing, and energy use will be required.

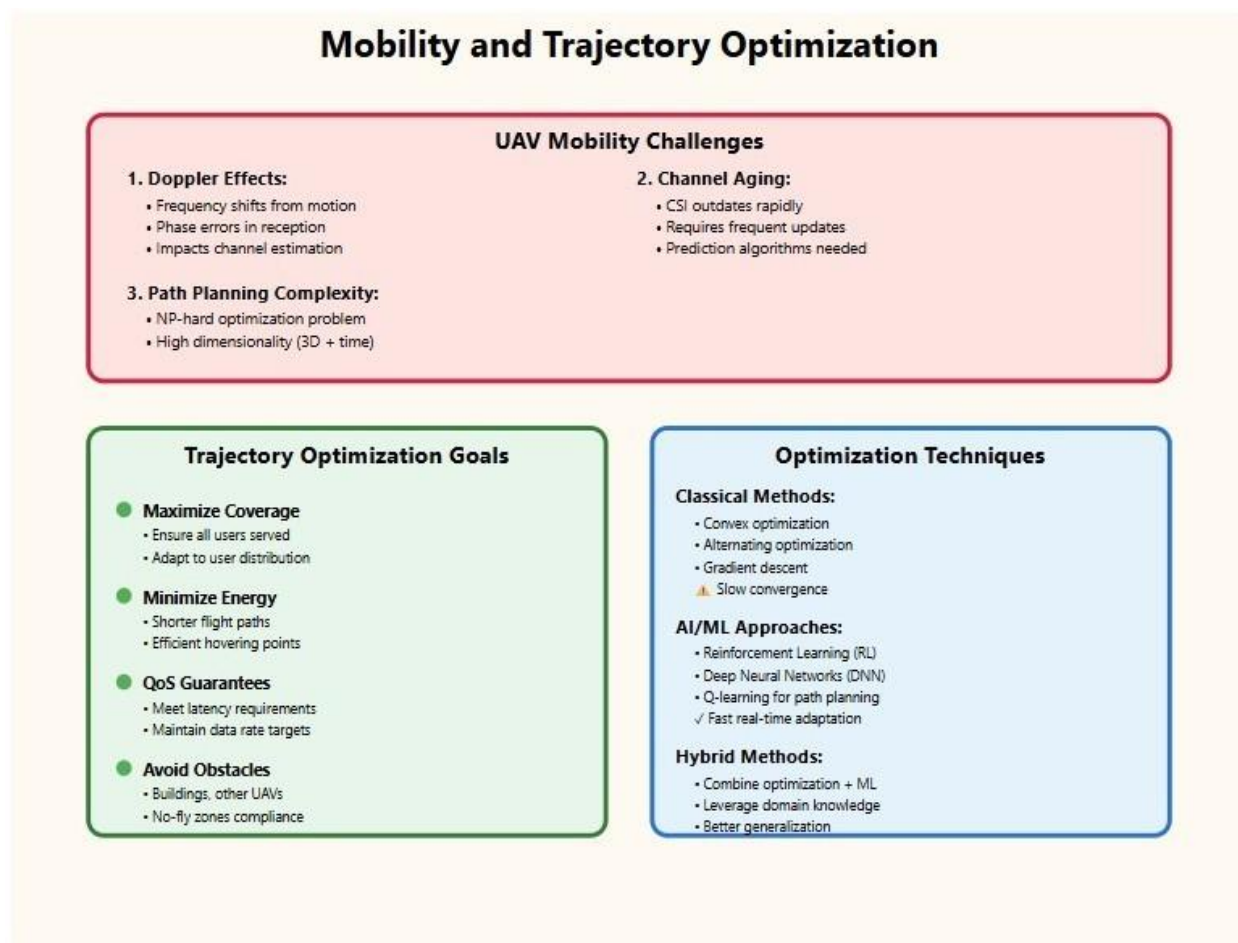


Fig. 9. Mobility and Trajectory Optimization.

D. Channel Modeling and Estimation

Accurate channel modeling for RIS-UAV-CF-mMIMO systems remains a fundamental challenge and is important for reliable system design. The UAV mobility, RIS programmability and distributed CF-mMIMO operation, jointly, result in channels that change quickly in space and time. This is different from the conventional terrestrial cellular networks where the channel behavior is relatively stable and can often be characterized by well-established models like 3GPP TR 38.901. These channels suffer from urban blockages, UAV motion, reflections from rooftops and surrounding structures, near-field effects for large RIS surfaces, Doppler shifts that can reach several kHz at high UAV speeds, and cascaded multi-hop paths (e.g., AP \rightarrow RIS \rightarrow UAV \rightarrow UE). Such effects introduce complex spatial correlations, abrupt LoS/NLoS transitions and additional phase rotations that make traditional stationary or single-hop models insufficient.

The UAV mobility leads to variations in altitude, acceleration, turning motion and orientation, resulting in fast channel aging and non-stationary fading statistics. In high-mobility scenarios such as urban roads, high-speed rail corridors or low altitude aerial platforms, the CSI can become outdated in a few milliseconds. Furthermore, the environment can be reshaped by RIS panels that allow element level control of reflection/transmission, but at the cost of significantly increasing the channel dimensionality. For a RIS with N elements, cascaded links over the surface can result in up to N^2 effective parameters. When multiple RIS panels, L distributed APs, K users, and UAV trajectories over T time slots are considered together, the entire channel can be treated as a multi-dimensional tensor of size around $[K \times L \times U \times N \times T]$. This increase in dimensionality results in significant overhead for CSI acquisition, pilot signaling, and feedback.

The RIS operation makes the channel estimation more complex, as the surface is passive and cannot transmit its own pilots. Standard uplink or downlink training thus resorts to indirect approaches such as pilot reflection schemes, RIS phase sweeping, or cascaded pilot designs. These

methods may incur large overhead especially when the number of RIS elements is large or multiple RIS panels are deployed. Taking into account the cascaded channels, the overlapping reflected paths can increase the noise level and decrease the reliability of the channel estimation process. In CF-mMIMO, numerous distributed APs are expected to contribute RIS-assisted and direct signals in phase. Any small CSI mismatches caused by quantization, feedback delay, or Doppler can degrade precoding gains, increase interference, and limit the macro-diversity the system is designed to offer. At terahertz frequencies, the challenges are amplified due to molecular absorption, beam squint and the requirement for nearfield modeling.

Dynamics induced by UAV add another layer of difficulty. For high Doppler spreads and fast geometry changes, CSI needs to be accurate and predictive. Conventional estimators such as LS or MMSE are not well suited for rapidly changing and non-stationary channels. Stochastic geometry models commonly used for terrestrial networks are not able to fully capture altitude-dependent scattering or UAV-specific propagation effects. High fidelity raytracing can provide accurate channel predictions but at a large computational cost and the need for detailed 3D models, thus rendering real time use impractical.

Hence, novel approaches for scalable and adaptive CSI acquisition are needed. Compressed sensing reduces training overhead by exploiting the sparsity of the angular and delay domains, however its performance is sensitive to the accuracy of the dictionary learning and robustness to mobility. Historical CSI, UAV motion data, and digital twin information can be used by recurrent networks, transformers, or graph neural networks to predict channel evolution, which enables proactive beamforming and RIS control. Reinforcement learning based methods can select pilot sequences or RIS configurations to minimize the estimation error while meeting the latency and energy requirements. A promising middle ground is offered by hybrid methods that combine simplified physical models with data-driven corrections.

Front haul load management techniques include feedback compression, federated aggregation of the CSI across the APs, and training sequences embedded directly in the RIS phase updates. For multi-UAV systems, cooperation for sharing the partial channel information can increase the spatial sampling density and track the fast-varying components better. Eventually, standardization work will need RIS-oriented reference signals, cascaded CSI formats, and mobility-aware tracking procedures.

In summary, effective channel modeling and estimation are important for RIS-UAV-CF-mMIMO systems. Reliable, low-latency and predictive CSI is critical for the efficient operation of distributed precoding, interference control and ISAC functions. The path forward will likely be a combination of physics-based modelling, machine learning tools, and adaptive estimation frameworks that can handle the complex and ever-changing environments expected in 6G networks.

E. Security and Privacy

- Due to the openness of wireless channels and the fact that UAV-assisted links travel through space instead of being placed on the ground, they are highly vulnerable to security threats, such as jamming, spoofing and eavesdropping. Due to their high altitude and large coverage area they are particularly attractive to attackers that want to disturb communication or tap confidential data. RIS can be employed to enhance the physical layer secrecy through techniques such as directional beam control, null-space transmission, and artificial noise injection. However, RIS also opens new avenues for attacks. For example, if a RIS controller is compromised, it can be exploited to misdirect signals, intentionally weaken links, generate harmful interference or leak information. This risk is more severe in CF-mMIMO settings where a large number of RIS panels and UAVs are coordinated together, increasing the number of components that need to be protected.

- To mitigate these risks, the system requires secure procedures for setting RIS parameters so that phase shift patterns cannot be modified by unauthorized parties. This includes the light but reliable authentication between the RIS controller, UAV and the central processing

unit (CPU). Moreover, in highly dynamic scenarios simple static keys may not be trustworthy anymore, and thus strong key management is required to secure communication between distributed APs, UAVs and RIS nodes. Recent ideas like blockchain based trust frameworks, quantum key distribution (QKD), federated authentication is being explored to improve resilience against advanced attacks. In parallel, AI-based anomaly detection [230] can be used to monitor RIS-UAV deployments in real-time and identify suspicious activities that may indicate spoofing, jamming, or unauthorized reconfiguration.

- In conclusion, RIS-aided UAV-enabled CF-mMIMO systems offer new chances to enhance the physical-layer security of 6G networks, but also call for a well-designed security framework to address the vulnerabilities in the hardware, software, and communication stack. Joint design of physical-layer secrecy techniques and higher layer cryptography, supported by measures such as secure UAV path planning and cooperative jamming will be important to achieve strong, secure, and persistently available 6G links.

F. Scalability and Computational Complexity

- Designing next-generation wireless systems involves solving the hard and computationally heavy problem of jointly optimizing the UAV trajectory, RIS phase shifts, and CF-mMIMO beamforming. The problem has a large number of variables due to the simultaneous control of many distributed antennas, RIS elements and UAV motion parameters. The optimization landscape is also highly non-convex, since the channel and the best RIS configuration are both affected non-linearly by changes in the UAV position. Standard convex optimization tools and simple heuristics are often unable to cope with this scale and structure, particularly when strict delay and reliability constraints are imposed by real-time 6G applications.

- Classical approaches such as alternating optimization, successive convex approximation or gradient-based heuristics can be used to find feasible solutions, but they typically have slow

convergence, get stuck in local optima, and do not scale well with the number of APs, users, or RIS elements. This limits their use in highly dynamic conditions where UAVs and users keep moving and RIS settings have to be updated frequently. To tackle these issues, several recent works explore machine learning (ML) and artificial intelligence (AI) based approaches that learn data driven policies adapted to specific environments. For example, reinforcement learning (RL) can enable UAVs to adapt their trajectories on the fly, while deep neural networks (DNNs) can approximate good RIS beam patterns without exhaustive search.

- Learning-based methods have obvious disadvantages. They can often produce faster and near-optimal decisions than purely model based schemes. However, they tend to need large training datasets, high processing power and careful design to avoid overfitting to a narrow set of operating conditions. Their behavior in unexpected situations is still an issue: an ML model that works well under normal operation may fail when it encounters unusual interference, hardware malfunctions, or deliberate adversarial actions. Therefore, finding solutions that balance performance, flexibility and computational cost remains an open research question.

- In the future, hybrid schemes which blend model-based optimization and data-driven learning are becoming more prominent. These approaches utilize analytical system models where they are accurate and employ AI tools to speed up convergence or deal with uncertainty. Another candidate is federated learning (FL), which enables UAVs and distributed APs to train shared policies without exposing raw data, which is good for privacy and reduces signaling load. Finally, these methods still require real-time implementation and hardware testing to ensure they can work reliably in practical 6G deployments.

G. Standardization and Deployment Issues

Standardization for RIS-assisted UAV communication is still in its infancy. The current 3GPP releases (up to Release 19) contain initial studies on non-terrestrial networks (NTN), distributed MIMO, and reconfigurable surfaces,

but detailed RIS procedures have not yet been specified. Some aspects are not specified, such as signaling for phase configuration, switching between the reflection modes, CSI reporting for cascaded channels, and methods for over-the-air RIS calibration. There is no common format for reporting RIS capabilities, no dedicated control channel for phase updates, and no unified interface between gNB control unit and RIS controllers. Thus, early prototypes are based on vendor specific implementations which may hinder interoperability. Likewise, current efforts on UAV integration still do not have clear standards on how to signal trajectories, how to provide mobility support for flying access points, and how to make handoff between aerial and terrestrial segments. This makes it hard to scale from small experimental setups to larger systems. The deployment in the real world also poses regulatory and operational issues that are not fully captured in the theoretical models. UAV flights are subject to aviation rules from national agencies (e.g. FAA, EASA, or CAAC) that impose maximum altitude limits, limit access to sensitive airspace, require visual or beyond-visual-line-of-sight approval, mandate remote identification, and define procedures for fault or emergency situations. Such rules restrict the paths available to the UAVs and affect the continuity of service and the cost of operation. Another source of variability is radio spectrum policy. Sub-6 GHz bands are already crowded, while mm Wave and terahertz bands, which are attractive for high-capacity RIS-UAV links, are still under regulatory uncertainty and often share frequencies with satellite or radar services. From the hardware standpoint, large tunable Meta surfaces that can be deployed outdoors are still in their infancy: they are not yet commercially available, can be expensive to manufacture and currently lack well-established safety guidelines for long-term exposure to electromagnetic fields.

Thus, a major open problem is to bridge the gap between analytical studies and deployable systems. Many research papers assume ideal phase control, perfect or near perfect CSI and highly flexible UAV motion. However, the gains predicted by these models can be severely reduced in practice,

due to phase quantization, signaling delays, airspace constraints, and hardware imperfections. Current field trials of RIS-UAV configurations are typically small in scale and short in duration, leaving little evidence on long-term reliability, cross-vendor interoperability, or operation alongside commercial 5G networks. In the future, increased cooperation between industry and academia will be necessary to develop shared test platforms, high-fidelity simulation tools and pilot deployments in real scenarios such as smart-city zones, rural connectivity projects and public-safety communication systems.

Overall, the numerous different issues that need to be tackled before RIS-assisted UAV-enabled CF-mMIMO systems can be deployed at large scale include hardware constraints, energy limitations, channel variation due to mobility, algorithmic complexity, security requirements, and the lack of mature standards. Progress will require improved hardware for RIS panels and UAVs, reliable channel estimation and beamforming techniques with reduced training and feedback, energy-aware control policies for propulsion and radio links, protection mechanisms for control signaling and user data, and coordinated standardization efforts in organizations such as 3GPP, ITU, IEEE and ETSI. Only with consistent progress on all these fronts will these architectures be able to progress from theoretical proposals to practical, large-scale deployments in future 6G networks. Altogether, hardware constraints, energy limitations, channel variation due to mobility, algorithmic complexity, security requirements, and lack of mature standards show the number of different issues to be addressed before the large-scale deployment of RIS-assisted UAV-enabled CF-mMIMO systems. Progress will require improved hardware for RIS panels and UAVs, reliable channel estimation and beamforming techniques with reduced training and feedback, energy-aware control policies for propulsion and radio links, protection mechanisms for control signaling and user data, and coordinated standardization efforts in organizations such as 3GPP, ITU, IEEE and ETSI. Only by moving forward in all these directions will these architectures be able to evolve from

theoretical proposals to practical, large-scale implementations in the future 6G networks.

IV. APPLICATION DOMAINS

➤ **URLLC (Ultra-Reliable Low-Latency Communication):** Very low delay and very high reliability for time-critical tasks such as autonomous driving, industrial automation, telesurgery and emergency response is a major goal of 6G. UAV relays can support URLLC by establishing aerial links that can adapt to variations in user density, mobility, and sudden traffic bursts. Combined with RIS, controlled reflections, focused beams, and better interference management can improve the coverage of UAVs and keep LoS paths stable even in cluttered environments. This scheme reduces effective propagation lengths, prevents overloading of ground paths and stabilizes radio channel. The 3D mobility freedom of UAVs and the RIS-based channel control make it easier to meet the stringent delay and reliability requirements of URLLC [44].

➤ **Massive IoT:** Massive IoT refers to very large numbers of low power devices deployed in smart cities, agriculture, logistics and health monitoring. Traditional cellular networks are often faced with problems of network scaling, interference and power consumption when pushed to support such dense deployments. By boosting weak links, steering coverage toward active zones and reducing unwanted interference, RIS assisted CF-mMIMO can address these issues. UAVs can act as mobile APs or as platforms carrying the RIS panels that can move to extend coverage in crowded or remote IoT areas. This allows the network to create energy-aware communication paths that are in line with the limited battery capacity of many IoT devices. The mobility of UAVs also enables data collection from sensors in places that are difficult to cover with fixed infrastructure, thus decreasing the deployment costs, and allowing an energy-aware operation of the whole system [42].

➤ **Edge Sensing and Communication:** Future 6G systems are expected to support sensing and communication over the same infrastructure. UAVs with radio units and RIS panels can serve

as aerial sensing platforms. They can fly over areas of interest to do real-time monitoring. They can be used for disaster assessment, traffic supervision, precision farming and they can also forward the user data. RIS can direct the reflected signals towards specific sensing targets or suppress interference from surrounding objects, which is beneficial to enhancing the measurement quality and reliability. The UAV can be equipped with edge computing capabilities that enable some of the sensed data to be processed locally, reducing the backhaul load and accelerating decisions for time critical applications such as wildfire detection or urban safety monitoring [39]. The real-time AI-based traffic surveillance also illustrates the need for low-latency sensing and communication in smart transportation environments, where RIS-assisted UAV-enabled CF-mMIMO can provide aerial monitoring, edge data collection, and reliable connectivity [221].

➤ **Physical Layer Security:** The networks are getting denser and more heterogeneous and this leads to more concerns about data privacy and integrity, especially for UAV-based links which transmit signals in the open air and can be intercepted or disturbed relatively easily. RIS-aided beamforming can provide spatial control to reduce signal leakage to unintended receivers. UAV

movement can also contribute to this by changing the flight path to avoid suspected eavesdropping or limiting exposure in sensitive areas. The secrecy performance can be further enhanced by artificial noise, cooperative jamming, and protected RIS controlling interfaces. At the same time, new vulnerabilities appear, such as the possibility of unauthorized RIS reconfiguration or malicious UAV route changes, which require stronger key management, authentication methods and secure update procedures. RIS and UAVs jointly provide a viable toolset for physical layer security that is aligned with the needs of future 6G systems [43].

A. Spectral Efficiency (SE)

The spectral efficiency (SE) in RIS-aided UAV-enabled CF-mMIMO systems is highly dependent on the number of RIS elements, as larger panels enable more precise control of reflections and beam shaping. But results reported in [45] show that SE does not continue to improve with element count. After about 128 elements the gain starts to flatten out. This behavior is mostly attributed to practical factors, such as the overhead of additional channel estimation, the limited phase-resolution of the control circuits and the extra processing required to handle very large RIS arrays. These points imply that the addition of elements alone is not a sustainable method to increase SE.

Table 1 KEY DESIGN CHALLENGES IN RIS-ASSISTED UAV-ENABLED CF-mMIMO SYSTEMS

Design Challenge	Description
Channel State Information (CSI) Acquisition	High UAV mobility and passive RIS elements necessitate advanced algorithms for precise channel estimation [41].
RIS Configuration	Real-time optimization of phase shifts and reflection coefficients requires significant computational resources [36].
UAV Path Planning	Trajectories directly impact beam quality, latency, and coverage, demanding sophisticated optimization techniques [38].
Joint Resource Allocation	Coordinated management of spectrum, power, RIS elements, and flight time is essential for optimal performance [42].
Security and Interference Management	Beamforming must minimize interference and secure data against eavesdropping in dynamic environments [43].

The other way is to deploy several RIS panels in different locations in the network instead of one huge surface. Placement of multiple smaller panels

in a judicious way can improve the SE by exploiting the spatial diversity and covering the blocked areas while enabling flexible

configurations in ground and aerial environments. At the same time, such multi-RIS setups also bring new issues such as interference between the panels, tight timing and phase alignment, and a much larger configuration space for phase control. This motivates the use of more advanced optimization methods, such as distributed schemes and learning-based algorithms, to reach good operating points within practical time and complexity constraints. In the case of RIS panels mounted on UAVs, there is an additional degree of control, since they can be repositioned to track the user movement and the changes in the traffic load. Overall, sustained SE improvements depend not only on panel size, but also on careful system design accounting for the number of RIS units, their layout, placement strategy and coordination inside CF-mMIMO architectures [46].

Secrecy Rate vs. UAV Position

The relative positionings of UAVs, legitimate users, access points (APs) and potential eavesdroppers with respect to each other significantly impact the secrecy performance of RIS-assisted UAV-enabled CF-mMIMO systems. Previous studies have shown that the deployment of the UAV at a location that is approximately the same distance from the users and the serving APs can often improve the secrecy rate. In this case, the desired links remain low path loss links but it is harder for the eavesdropper to obtain a clear geometric advantage. Such a spatial balance reduces the likelihood of a successful interception, and it minimizes information leakage.

It is not easy to put these “good” placements into practice. UAVs are constrained by motion limits, limited battery capacity, airspace rules, and physical obstacles. In an ultra-dense urban environment, for example, buildings may block the line-of-sight (LoS) paths, therefore it is difficult to stay at the positions predicted by theoretical models. RIS panels can be used to reshape the radio environment, by creating paths that reinforce the desired links while weakening the unwanted exposure. Directional transmission and jamming strategies can also be incorporated into the RIS-UAV design such that confidential data is directed to the intended users, while artificial

noise is directed towards nodes that are expected to behave as eavesdroppers. Another challenge is that the gains in secrecy rate must be traded off against other performance metrics such as energy consumption, spectral efficiency, and delay. In practice, the path planning, RIS configuration, and beamforming need to be selected such that the secrecy is not compromised at the expense of the overall system performance. Secrecy-friendly UAV placements may result in longer routes, more hovering time, more energy consumption and less flight endurance. Recent works started to jointly optimize UAV trajectories, RIS phase patterns, and CF-mMIMO beamforming using machine learning and reinforcement learning to enhance secrecy without sacrificing overall performance. In summary, the security of UAV-enabled RIS assisted CF-mMIMO networks requires not only careful geometric placement, but also multi-objective optimization tools that can adapt to different channel and traffic conditions in future 6G systems [43].

Outage Probability

The mobility patterns of the UAV significantly affect the outage probability in RIS-assisted UAV-enabled CF-mMIMO systems. Simulation results show that smooth curvature-controlled flight paths can greatly reduce outage probability for a wide range of mobility conditions. On the other hand, rapid channel variations are caused by abrupt maneuvers or irregular paths that can break line-of-sight (LoS) links, increase Doppler shifts and cause more frequent handovers. These effects reduce the benefits of cooperative beamforming from distributed access points and make it more difficult to maintain the accuracy of the RIS phase settings. When UAVs move along smoother trajectories, the channel changes at a slower rate, which leads to more reliable CSI estimation and limits error build-up in real-time beamforming updates.

Easier motion also aids in energy utilization and flight endurance. UAVs require more power and thrust for sharp turns and fast altitude changes, while gradual changes in the path allow them to change position with less energy. This is especially important given the limited battery capacity of

typical UAV platforms. Coordinated smooth trajectories in multi-UAV scenarios can also reduce the probability of mutual interference or unintended shadowing, especially in dense areas where reflections and blockages are common.

At the network level, stable UAV motion guarantees quality-of-service for a wide range of use cases, including delay-sensitive services such as URLLC and large-scale IoT connectivity. Studies have shown that well-designed smooth trajectories can reduce the outage probability by about 30-40% compared to random or non-optimized movement patterns. Machine learning and predictive control methods can further increase these gains by allowing UAVs to predict channel variations and to change their paths in advance, as well as to coordinate with the RIS panels and the CF-mMIMO access points to ensure that the performance remains stable over time [38].

V. LITERATURE MATRIX AND COMPARATIVE ANALYSIS

In this section, we propose a systematic literature matrix and a comparative analysis of recent works on RIS-assisted UAV-enabled CF-mMIMO systems for 6G wireless communications. As the integration of RIS, UAVs, and CF-mMIMO is a new research area, the literature under review is divided into several related research streams. These include RIS-assisted CF-mMIMO, UAV-enabled CF-mMIMO, UAV-mounted RIS communication, STAR-RIS-assisted, energy efficient cell-free, physical layer security, channel modeling, hardware impairments, NOMA and IoT integration, and AI-assisted resource optimization. This organization helps to identify how individual technologies have evolved and how they can be combined into a cohesive 6G architecture.

Table 2 KEY DESIGN CHALLENGES IN RIS-ASSISTED UAV-ENABLED CF-mMIMO SYSTEMS

Design Challenge	Description	Impact on System Performance	Related References
Channel State Information Acquisition	CSI estimation becomes difficult because RIS elements are mostly passive, UAV links are mobile, and CF-mMIMO depends on cooperation among many distributed APs.	Increases pilot overhead, causes outdated CSI, reduces beamforming accuracy, and limits coherent joint transmission.	[20], [41], [70], [90], [149], [155], [160], [172]
RIS Phase Configuration	RIS phase shifts, reflection coefficients, and element grouping must be adjusted according to channel quality, user location, AP cooperation, and UAV movement.	Poor RIS tuning reduces spectral efficiency, weakens interference control, and lowers coverage gains in blocked regions.	[37], [40], [45], [147], [159], [167], [174]
UAV Location and Trajectory Planning	UAV altitude, position, velocity, and flight path strongly affect LoS probability, path loss, Doppler shift, link stability, and energy use.	Non-optimized UAV trajectories increase outage, latency, propulsion energy, and handover complexity.	[38], [53], [54], [76], [84], [93], [106], [162], [181]

Joint Beamforming and Resource Allocation	Active AP beamforming, passive RIS beamforming, user scheduling, power control, and UAV movement must be jointly optimized.	Creates high-dimensional and non-convex optimization problems that are difficult to solve in real time.	[22], [26], [40], [90], [142], [147], [148], [152]
Energy Efficiency	UAV propulsion, RIS control circuits, AP cooperation, fronthaul transmission, and onboard computation all contribute to total energy consumption.	Limits UAV endurance and affects the sustainability of large-scale 6G deployment.	[47], [55], [81], [127], [133], [144], [187]
Hardware Impairments	Practical RIS panels suffer from phase quantization, reflection loss, mutual coupling, EMI, imperfect hardware, and calibration errors.	Reduces the gap between ideal simulation results and real deployment performance.	[48], [67], [85], [103], [124], [149], [180], [188], [189]
Mobility and Channel Aging	UAV movement, user mobility, Doppler shift, and fast topology changes make the channel time-varying and non-stationary.	Causes channel aging, outdated precoding, beam misalignment, and loss of macro-diversity gains.	[20], [41], [76], [92], [93], [112], [155], [170]
Security and Privacy	UAV links are exposed to eavesdropping, spoofing, jamming, and malicious RIS controller attacks.	Requires physical layer security, secure RIS configuration, cooperative jamming, and authentication mechanisms.	[32], [43], [96], [120], [129], [150]
Scalability and Computational Complexity	Large numbers of APs, RIS elements, UAVs, and users increase signaling, fronthaul load, and optimization complexity.	Makes centralized optimization expensive and motivates scalable, distributed, and learning-based methods.	[69], [72], [73], [74], [75], [79], [82], [134], [135]
IoT, NOMA, and Multiple Access Integration	Massive IoT and NOMA require efficient support for many low-power users and dense device access.	Increases interference and scheduling complexity but improves connectivity when combined with RIS and CF-mMIMO.	[34], [42], [49], [63], [75], [116], [125], [153], [172]
THz and High-Frequency Operation	THz and mmWave links can support very high data rates but suffer from severe blockage and path loss.	RIS and UAVs can help restore connectivity, but beam alignment and near-field modeling become difficult.	[87], [111], [152], [179]

Standardization and Deployment	Practical deployment requires standard RIS control, UAV airspace coordination, CSI reporting, fronthaul and protocols, and interoperability.	Lack of standards limits field testing, cross-vendor implementation, and large-scale deployment.	[6], [9], [188], [189], [207]
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Table 2 presents the major design challenges reported in the reviewed literature. These challenges are indicative of the fact that RIS-assisted UAV-enabled CF-mMIMO can provide improved coverage, spectral efficiency, energy efficiency, and reliability but its practical deployment depends on solving numerous coupled problems. They include channel state information acquisition, RIS phase control, UAV

trajectory optimization, distributed AP cooperation, resource allocation, energy management, security, scalability, and standardization. The main difficulty is that these problems are not independent. UAV movement changes the channel, RIS configuration changes the propagation environment, and CF-mMIMO beamforming relies on accurate and timely CSI across many distributed APs.

Table 3 LITERATURE MATRIX FOR RIS-ASSISTED UAV-ENABLED CF-mMIMO SYSTEMS

Research Category	Representative References	Main Focus	Main Contribution	Main Limitation or Research Gap
Foundational CF-mMIMO surveys and architectures	[2], [19], [66], [69], [72], [73], [75], [77], [79], [98], [124], [134]	Distributed AP cooperation, user-centric service, fronthaul, scalability, and signal processing	Establishes CF-mMIMO as a strong architecture for improving coverage uniformity, reducing cell-edge problems, and supporting massive connectivity	Does not fully address RIS-assisted propagation control or UAV-enabled aerial mobility
RIS-assisted CF-mMIMO communication	[24], [29], [37], [40], [45], [46], [50], [52], [57], [61], [70], [71], [83], [147], [159]	RIS phase design, AP cooperation, beamforming, and performance analysis	Shows that RIS can improve spectral efficiency, coverage, interference control, and cell-edge service in cell-free systems	Often assumes fixed RIS panels, ideal CSI, and simplified hardware models
Energy-efficient RIS-aided CF-mMIMO	[47], [55], [59], [144], [160], [167]	Energy efficiency, power allocation, AP selection, and RIS-assisted green networking	Demonstrates that RIS can reduce transmit power and improve energy-aware operation in cell-free networks	UAV propulsion energy and RIS control energy are often not jointly modeled

Multi-RIS and distributed RIS in CF-mMIMO	[24], [29], [45], [57], [126], [164], [174]	Multiple RIS panels, distributed RIS deployment, and network-level coordination	Investigates whether multiple RIS panels improve rate, fairness, and coverage in cell-free systems	More RIS panels can increase control overhead, CSI burden, and deployment complexity
Active RIS and STAR-RIS-assisted CF-mMIMO	[7], [8], [48], [60], [67], [85], [103], [107], [109], [116], [120], [122], [129], [130]	Simultaneous transmission and reflection, active RIS gain, and two-sided coverage	Enhances service coverage and spatial flexibility by supporting users on both sides of the surface	Active and STAR-RIS designs increase hardware complexity, power use, and control requirements
UAV-assisted CF-mMIMO and aerial cell-free systems	[21], [22], [54], [76], [84], [87], [91], [92], [93], [95], [99], [106], [112], [137], [175]	UAVs as aerial APs, UAV placement, aerial access, and air-ground coordination	Shows that UAVs can extend coverage, support emergency service, and improve LoS connectivity in cell-free systems	RIS-assisted channel control is not always integrated, and UAV energy limits remain critical
RIS-assisted UAV communication	[9], [10], [11], [18], [36], [39], [56], [78], [108], [109], [140], [141], [145], [150], [154], [163], [170], [187], [197], [207], [214]	UAV-mounted RIS, aerial RIS, UAV relays, LoS enhancement, and blockage mitigation	Demonstrates that RIS can improve UAV communication links, extend coverage, and reduce path loss in difficult environments	Many studies do not include full CF-mMIMO cooperation or distributed AP coordination
Joint RIS-UAV-CF-mMIMO systems	[16], [17], [38], [53], [88]	Joint RIS assistance, UAV trajectory, and cell-free MIMO communication	Provides direct evidence that combining RIS, UAVs, and cell-free cooperation can improve downlink performance and link reliability	Still limited in number and often simulation-based with simplified CSI, energy, and hardware assumptions
Physical layer security in RIS-UAV-CF-mMIMO	[32], [33], [35], [43], [96], [120]	Secrecy rate, eavesdropping resistance, artificial noise, secure beamforming, and UAV-aided secrecy	Shows that RIS and distributed APs can enhance secure transmission through controllable propagation and cooperative beamforming	Practical protection of RIS controllers, UAV control links, and fronthaul security remains underexplored

IoT, mMTC, and symbiotic radio integration	[42], [49], [58], [63], [101], [102], [127]	Massive IoT, symbiotic radio, aerial IoT, and energy-aware connectivity	Supports dense low-power device connectivity and flexible coverage for massive IoT scenarios	Mobility, battery lifetime, and practical scheduling for large-scale IoT remain difficult
NOMA, NGMA, and multiple access integration	[34], [75], [86], [97], [116], [118], [125], [153], [172], [196]	NOMA, NGMA, RIS-assisted access, and multi-user transmission	Improves spectrum sharing and user access in dense 6G networks	Joint optimization with UAV mobility and CF-mMIMO cooperation remains complex
ISAC, sensing, and edge intelligence	[5], [51], [64], [81], [111], [121], [123], [131], [132], [185], [205]	Integrated sensing and communication, MEC, federated learning, task offloading, and edge intelligence	Connects RIS-UAV-CF-mMIMO with future 6G services such as sensing, computation, and intelligent control	Requires joint design of communication, sensing, computing, and energy resources
Channel modeling, channel aging, and imperfect CSI	[20], [25], [30], [41], [50], [67], [70], [90], [155], [159], [160], [179]	Cascaded CSI, channel aging, spatial correlation, ray tracing, and imperfect CSI	Highlights the importance of realistic channel models and robust beamforming in RIS-assisted systems	Scalable CSI acquisition for mobile UAV-RIS-CF-mMIMO remains unresolved
AI-assisted optimization and learning-based control	[27], [31], [78], [81], [135], [181], [187]	Deep learning, reinforcement learning, trajectory control, and AI-based resource management	Reduces online optimization burden and supports adaptive control in dynamic environments	Requires large training data, reliable generalization, and explainable decision making
THz, mmWave, NTN, and space-air-ground integration	[1], [9], [87], [95], [111], [139], [152], [188], [189]	High-frequency communication, NTN, aerial connectivity, and space-air-ground networks	Extends RIS-UAV-CF-mMIMO toward broader 6G scenarios with high capacity and wide-area coverage	High path loss, beam alignment, hardware constraints, and standardization remain major barriers
Hardware-aware RIS and practical implementation	[6], [67], [85], [103], [124], [149], [180], [188], [189], [192], [193], [199]	RIS hardware, phase errors, electromagnetic interference, metasurface design, and practical constraints	Moves RIS research closer to real deployment by addressing non-ideal hardware behavior	Experimental testbeds and long-term field validation are still limited

Table 3 provides a literature matrix of main research contribution. If we look at the representative studies grouped according to their works we see three important patterns. First, CF-

mMIMO has been extensively explored as a distributed and user-centric architecture, but many basic studies do not consider RIS or UAVs. Second, the results of RIS-aided CF-mMIMO studies clearly show gains in terms of energy efficiency, coverage and spectral efficiency, but they typically assume a fixed RIS deployment and ideal channel knowledge. Third, UAV-assisted and UAV-RIS studies have the mobility and flexible coverage features, but few works have considered the full integration of UAV mobility with RIS configuration and CF-mMIMO cooperation. This implies that the entire RIS-UAV-CF-mMIMO architecture remains an emerging research direction.

The comparative analysis yields a number of findings. First, CF-mMIMO has a mature theoretical basis, with strong support for

distributed AP cooperation, user-centric service and better coverage uniformity. However, the addition of RIS and UAVs makes the system more flexible but hard to optimize. Second, RIS-aided CF-mMIMO studies always report improvements in spectral efficiency, energy efficiency and coverage, but many of them rely on unrealistic assumptions, such as perfect CSI, continuous phase control and static RIS placement. Third, UAV-assisted studies emphasize the importance of aerial mobility; nevertheless, the UAV trajectory optimization is strongly coupled with energy consumption, Doppler effects, payload limitations, and regulatory constraints. Fourth, the joint studies on RIS, UAVs and CF-mMIMO are still limited compared with the wider literature on each individual technology.

Table 4 COMPARISON OF RIS MODES IN CF-mMIMO SYSTEMS

RIS Type	Operation	Advantages	Limitations
Passive RIS	Reflects signals only	Low cost, low power	Limited control, no amplification
Active RIS	Includes amplifiers	Compensates path loss	Higher cost, more power use
STAR-RIS	Transmit + Reflect simultaneously	Dual coverage, higher SE	Complex design, synchronization issues

Table 5 ROLES OF UAVS IN RIS-ASSISTED CF-mMIMO SYSTEMS

UAV Role	Function	Benefit
UAV as AP	Acts as mobile access point	Expands coverage in remote areas
UAV as Relay	Forwards signals between APs and users	Reduces blockage &
UAV as RIS Carrier	Mounts RIS panels	Enhances LoS connectivity

Table 6 COMPARATIVE FEATURES OF RIS, UAV, AND CF-mMIMO IN 6G NETWORKS

Feature	RIS	UAV	CF-mMIMO
Main Function	Beam steering	3D coverage	Distributed access
Key Advantage	Energy/spectral efficiency	Mobility, flexibility	Uniform user experience
Challenge	Hardware complexity	Limited energy	Fronthaul coordination
Role in 6G	Smart environment	On-demand connectivity	Large-scale cooperation

Another important observation is the evolution of the literature from isolated optimization problems to integrated system design. The previous works focused on one objective like maximizing sum rate, improving secrecy rate or minimizing transmit power. Recent studies are increasingly

concerned with multi-objective design such as energy efficiency, security, resource allocation, edge computation, sensing and hardware impairments. This trend matters because practical 6G systems will not optimize a single metric only. Instead they have to make tradeoffs between

coverage, latency, reliability, energy consumption, computational complexity and deployment cost.

Table 7 CATEGORIAL COMPARISON OF RIS, UAV, AND CF-mMIMO IN 6G NETWORKS

Category	Challenge	Implication
Deployment	UAV trajectory optimization	Impacts coverage, energy usage
Channel Estimation	High-dimensional CSI acquisition	Increases overhead and latency
Energy	UAV power constraints	Shorter mission duration, recharge issues
Security	Eavesdropping and jamming	Requires physical layer security
Integration	RIS-UAV coordination	Complex scheduling and synchronization

Table 8 PERFORMANCE COMPARISON OF RIS-UAV-CFmMIMO, NON-RIS UAV-CFmMIMO, AND CONVENTIONAL MIMO

Metric		RIS-UAV-CFmMIMO	Non-RIS UAV-CFmMIMO	Conventional MIMO
Spectral Efficiency (bps/Hz)		18.5	12.4	9.8
Energy Efficiency (Mbps/W)		35.2	22.1	15.3
Latency (ms)		8.1	15.7	20.5
Coverage Probability		0.93	0.81	0.72

The literature also shows a clear gap between the theoretical performance and the practical implementation. Although many simulation-based works report large gains from RIS, UAVs or CF-mMIMO, the gains will be reduced when taking into account the channel estimation errors, RIS phase quantization, fronthaul limitations, UAVs battery constraints, synchronization errors and hardware impairments. Therefore, future research should focus more on the practical channel model, hardware-aware RIS design, low-overhead CSI acquisition, distributed optimization, and experimental validation. In particular, testbeds for RIS-assisted UAV-enabled CF-mMIMO are needed to verify if the theoretical gains can be achieved under realistic propagation, mobility and energy constraints.

Overall, the reviewed literature confirms that the RIS-assisted UAV-enabled CF-mMIMO is a promising architecture for 6G wireless networks.

RIS allows programmable propagation control, UAVs allow flexible aerial coverage, and CF-mMIMO allows distributed user-centric communication. Their integration can support applications like emergency networks, smart cities, massive IoT, remote connectivity, aerial communication, secure transmission, and integrated sensing and communication. Yet, the field is still developing, and the most crucial open problems are practical CSI estimation, joint trajectory and phase optimization, secure RIS and UAV control, scalable AP cooperation, energy-efficient operation, hardware-aware modeling, and standardization. To move from theoretical research to large-scale 6G deployment, RIS-assisted UAV-enabled CF-mMIMO systems need to overcome these challenges.

VI. TAXONOMY OF RESEARCH DIRECTIONS

➤ **AI-Driven Optimization:** Recent work has been applying machine learning and deep reinforcement learning to adjust RIS phases on the fly and control UAV paths in real-time so that the network can react to fast changes in channels and user movement [47].

➤ **Scalable Architectures:** The demand for system designs that can handle multiple UAVs and RIS panels simultaneously while retaining manageable coordination in large-scale and mixed 6G deployment scenarios is increasing [49].

➤ **Energy Efficiency:** A key research direction is to minimize the total power consumption including UAV propulsion, wireless transmission and RIS control, while providing reliable coverage and acceptable data rates [47].

➤ **Physical Layer Security:** The RIS-based beamforming and the mobility of UAVs can be exploited to improve the physical layer security by means of the control of the signal strength, the focusing of the energy on the legitimate users and the adjustment of the beams to lower the exposure to possible eavesdroppers [43].

VII. OPEN ISSUES AND FUTURE DIRECTIONS

➤ **AI-Driven Optimization:** The joint optimization of the UAV trajectories, the RIS phase settings, and the CFmMIMO beamforming results in large non-convex design spaces that are not easily handled by classical optimization tools alone. Artificial intelligence (AI) and machine learning (ML) methods including reinforcement learning, federated learning, and graph neural networks are applied to find good solutions within practical time and complexity limits. Open questions remain on how to design models that can scale to many users and nodes, adapt to fast channel variations and keep the computational cost manageable. Moreover, explainable AI (XAI) is of interest for the transparency of safety critical services such as URLLC and autonomous control [47].

➤ **Experimental Testbeds:** Despite the great progress in analytical and simulation-based methods, there are few experimental platforms

that integrate RIS, UAVs, and CF-mMIMO into one system. Many existing studies rely on simulations or small indoor setups which do not fully account for outdoor propagation, UAV mobility restrictions or realistic multi-user interference. Building larger outdoor testbeds with programmable RIS panels, UAV-based access points, and distributed CFmMIMO nodes would allow a direct assessment of throughput, latency, reliability, and energy consumption in realistic settings. Also, such testbeds can generate datasets for training and validating AI based algorithms, which is a partial solution to the data scarcity problem in RIS-UAV research [50].

➤ **Cross-Layer Protocol Design:** Most of the current works are focused on the physical-layer aspects, such as beamforming and channel estimation. However, in practice, novel designs at the MAC, network and transport layers are also required for RIS-assisted UAV-enabled CF-mMIMO. The scheduling procedures should consider the UAV motion and RIS update delays and the routing protocols should consider the UAV trajectories and battery limits. Cross-layer approaches are critical to ensure smooth operation and compatibility especially for use cases involving edge computing, large scale IoT data collection and URLLC traffic [51].

➤ **Cost-Effective Hardware:** Laboratory prototypes of RIS and STAR-RIS have been built and tested, but they are still quite expensive and not ready for large-scale deployment in real networks. There is a clear need for cheaper, less power-consuming, less space-consuming designs, still supporting features such as full-duplex operation in 6G settings. However, the installation of RIS panels on UAV introduces additional constraints such as payload constraints, battery capacity and flight stability that require lightweight structures and energy-aware hardware design. The solutions to these problems are an essential step for the transition of RIS-UAV-CF-mMIMO systems from research prototypes to practical field deployments [48].

➤ **Distributed Security Frameworks:** The wireless environment is highly exposed to UAV-assisted connections and thus vulnerable to jamming, spoofing and passive interception,

which makes security a major design concern. RIS-based beamforming is able to enhance the physical layer security by focusing energy to the legitimate users and reducing the leakage, but this advantage can be lost if the RIS controllers are misconfigured or hijacked or an attacker takes control of a UAV node. A natural line of work is the development of distributed security frameworks where multiple RIS units and UAVs cooperate. They can

maintain alternative secure paths, launch coordinated jamming towards suspected eavesdroppers, and use authentication schemes that go beyond conventional key-based methods. Two potential tools for securing such systems against large-scale cyber-physical attacks are blockchain-based trust management and federated learning for abnormal behavior detection [43]

Table 9 LITERATURE MATRIX FOR RIS-ASSISTED UAV-ENABLED CF-mMIMO SYSTEMS

Ref.	Authors	Focus Area	RIS Type	UAV Role	Key Insight
[1]	Abualhauja'a et al.	RIS on UAV	Passive	RIS Carrier	Aerial RIS enhances LoS connectivity for 6G [36].
[2]	Ma et al.	Beamforming	Static	-	Cooperative beamforming improves SE in CF-mMIMO [40].
[3]	Al-Nahhas et al.	Multi-RIS	Passive	-	Multi-RIS enhances SE but requires optimization [45].
[4]	Al-Nahhas et al.	RIS in CF-mMIMO	Passive	-	RIS improves competitiveness of CFmMIMO systems [46].
[5]	Lan et al.	IoT Networks	Passive	-	User-centric RIS-CF-mMIMO for IoT [42].
[6]	Zhang et al.	Energy Efficiency	Passive	-	RIS enhances energy efficiency in CFmMIMO [47].
[7]	Ma et al.	STAR-RIS	Active STAR	-	STAR-RIS boosts SE via dual reflection [48].
[9]	Zhang et al.	Trajectory Optimization	Passive	UAV-AP	Joint UAV-RIS optimization enhances coverage [38].
[14]	Dang et al.	Security	Reflective	UAV + RIS	RIS suppresses eavesdropping effectively [43].
[15]	Shi et al.	Channel Aging	Passive	AP	Channel aging degrades performance [41].

VIII. CONCLUSION

RIS-assisted UAV-enabled CF-mMIMO systems are emerging as a promising direction for 6G wireless networks, thanks to their flexibility and their ability to improve spectral efficiency, energy use, coverage, and physical-layer security. By combining the tunable behavior of RIS, the

mobility of UAVs, and the distributed structure of CF-mMIMO, these systems can adapt to difficult propagation conditions, lessen the impact of blockage and fading, and support a wide range of 6G applications.

Even with the progress seen in recent years, many questions remain, especially when moving from

small test setups to large, operational deployments. Open issues include the limited energy budget of UAVs, the need for lightweight and effective RIS hardware, and the joint design of UAV trajectories, RIS configurations, and CF-mMIMO precoding strategies. There is also a clear need for interoperable architectures and cross-layer protocols so that performance gains predicted by theory and simulation can be reproduced in real networks. Further advances will call for contributions from several fields, including signal processing, RF and antenna design, networking, and AI. Data-driven methods, better circuit and antenna solutions, and improved protocol stacks are all likely to play a significant role. With steady progress on these fronts, RIS-assisted UAV-enabled CF-mMIMO systems can move from concept to deployment and take on an important role in 6G networks, enabling use cases such as smart cities, disaster response, industrial automation, and other demanding wireless services.

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