Enhancing UAV-Based Public Safety Networks with Reconfigurable Intelligent Surfaces

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Abstract Recently, reconfigurable intelligent surface (RIS) has emerged as a 6G enabling technology, which is capable of enhancing communication reliability, extending coverage, and improving security, while maintaining high energy and spectral efficiency. RIS comprises a number of artificially engineered meta-atoms that achieve diverse functionalities, including beam shaping, signal splitting, reflection, absorption, and polarization. These functionalities shed the light on the advantageous integration of RIS into future wireless networks. Specifically, integrating RIS into unmanned aerial vehicle (UAV) networks can be attractive, in the sense that RIS and UAV networks are intertwined, i.e., being enabled by each other. In fact, RIS-equipped UAVs can flexibly move in the 3D space to achieve panoramic full-angle signals manipulation, while UAV users may rely on the available RISs within the environment in order to operate securely, at extended ranges, and with reduced communication and energy costs. Consequently, the integration of RIS with UAV networks is advocated as a key enabler for critical public safety services, where highly resilient, reliable, secure, and low latency communications are mandatory. In this chapter, we aim to articulate the fundamentals, design aspects, and applications of RIS as an enabling technology for future wireless networks. Furthermore, we will present an in-depth discussion about the integration of RIS into UAV networks, with emphasis on the mechanisms, advantages, and related challenges. Finally, practical

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public safety related use cases will be studied, providing performance insights and future research directions.

1 Introduction

The speculative vision of future sixth-generation (6G) wireless networks is tailored for provisioning massive-scale ubiquitous connectivity, with the aim to cater for the massive increase in the number of connected devices. This explosive growth is a consequence of the emergence of novel data-hungry applications, which require seamless on-demand wireless connectivity, with guaranteed high-reliability and ultra-low latency requirements [1]. Such applications call for the development of efficient technologies to provide enhanced connectivity, in order to cover wider areas at the earth, from urban and suburban to rural areas, and therefore, support a wider range of new use cases. Over the last decade, unmanned aerial vehicle (UAV) networks has attracted a considerable attention from the research and industrial communities. This stimulated from the evolution of aerial-based applications that are supported by UAV networks, including security inspection, packet delivery, traffic control, as well as connectivity support to rural and disaster-hit areas [2]. The ability of UAVs to fly in a three-dimensional (3D) space with flexible altitudes, in the range of few hundred meters, enables them to realize a 360° panoramic full-angle communication, and hence, provide on-demand backhaul connectivity to ground nodes, fronthaul links for aerial nodes, and an interface between satellite and ground networks. Energy efficiency constitutes a major limiting factor in the design of efficient UAV networks, given their limited on-board battery capacity, which limits the flying time between a few minutes and a few hours. This is particularly pronounced when the UAV acts as a flying base station (BS) or an amplify-and-forward (AF) relay, due to the increased amount of consumed power needed for signals generation, transmission, and processing. Extensive research efforts have approached the energy efficiency issue, with the aim to enable UAVs to enjoy uninterrupted long flying time and to widen the range of functionalities supported by flying BSs and relays.

Motivated by the recent advancement in the field of reconfigurable intelligent surfaces (RISs), RIS-enabled UAV networks have emerged as a promising candidate in order to realize energy-efficient, reliable, cost effective, and low-complex wireless communication at the sky [3]. In addition to the earlier mentioned features, the integration of RIS into aerial networks was motivated by other several advantages offered by these intelligent surfaces. Inspired by their basic operational principle, RISs promise to offer enhanced reliability to UAV-supported ground communication, by ensuring the availability of a line-of-sight (LoS) link between the UAV and terrestrial nodes. It is worth recalling that the existence of a LoS is essential for the realization of efficient aerial-ground communication. Such links might be unavail-

able or blocked by an obstacle, particularly in crowded urban areas. Furthermore, the utilization of an RIS, mounted at the UAV, enables the UAV to extend its coverage area, by employing a number of functionalities supported by the RIS, e.g., wave focusing and splitting. This attractive property can be significantly boosted by the employment of a larger number o reflective elements (REs), which are the main building blocks of an RIS [4].

1.1 RIS-Enabled UAVs for Public Safety Networks

Public safety networks are a critical type of wireless networks that are essential for emergency scenarios such as, fires or natural disasters, and are characterized by their fast deployment, guaranteed coverage and energy supply, availability, low latency, and adaptivity. UAV networks have been extensively studied in the literature as key enablers for public safety networks. This is motivated by the swift deployment, the availability of a line-of-sight (LoS) communication, the availability of on-demand 360° panoramic full-angle communication, and the scalability features offered by UAV systems, which perfectly fit the needs of public safety networks. Nevertheless, the limited battery capabilities and the short communication distances constitute a limiting factor in the deployment of UAV networks for public safety communications. In this regard, the integration of RIS into UAV networks represents an appealing solution for public safety systems. This is motivated by the seamless, flexible, wide-coverage, and reliable communication that can be offered by RIS-aided UAV networks to the first responders (FRs) when an emergency occurs, either in urban or rural areas. Furthermore, various RIS functionalities can be exploited to enable enhanced signal strength and hence, longer communication distances. Inspired by this, the aim of this chapter is to lay down the fundamentals of RIS-enabled UAV networks, as an enabler for resilient and low-latency communication in public safety networks. In particular, the main chapter contributions can be summarized as follows:

– Articulate the fundamentals of RIS-enabled wireless networks, in addition to a thorough discussion on metasurfaces, trade-offs between RIS and relaying systems, and path-loss modeling. In the latter, we investigated the 3GPP models for terrestrial and non-terrestrial networks.
– Study the integration of RIS into UAV wireless networks. In particular, we will shed lights on the fundamentals, advantages, and major limitations of RIS-assisted and RIS-equipped UAV systems.
– To demonstrate the performance of RIS-assisted and RIS-equipped UAV communications, we present two case studies as enablers for surveillance and search-and-rescue applications, where we investigate the related achievable data rate performance.
– We highlight potential limitations of RIS-enabled UAV networks and sketch the road-map toward future research directions.

2   Chapter Outline

This chapter is organized as the following. In Sect. 3, we present the fundamentals of RIS technology, an in-depth discussion about metasurfaces, and a thorough comparison between RIS-enabled and relaying networks. We further present the path-loss modeling, including the 3GPP model, of RIS-assisted wireless networks, for terrestrial and non-terrestrial scenarios. Section 4 extensively presents the basic principles, advantages, and limitations of the integration of RIS into UAV networks, with considering two scenarios, namely, RIS-assisted and RIS-equipped. The efficiency of adopting RIS-enabled UAVs as an enabler for public safety networks is demonstrated in Sect. 4, in which simulation results are presented. The chapter is concluded in Sect. 5 in which we highlight major challenges in RIS-enabled UAVs for public safety networks, and point out potential future research directions.

3   Reconfigurable Intelligent Surface

The ongoing deployment of the fifth generation (5G) wireless networks has raised serious debates on whether 5G networks will be capable of delivering the promising vision built over the last few years. Particularly, it has become evident that the advancements offered by 5G networks follow similar trends as the ones brought by their predecessors [1]. This means that, albeit the remarkable performance enhancement introduced, in terms of data rate, spectral and energy efficiency, connected devices, coverage, and capacity, to name a few, 5G wireless networks have failed to realize breakthrough technological trends that promised to capture the ever-growing stringent requirements of future wireless networks, which aim to enable ubiquitous, secure, unified, self-sustainable, and fully-intelligent platforms. Through the solidification process of the 5G standardization and commercialization, the lights were shed on the development of enhancing technologies for improved signals transmission and reception, with emphasis on the design of novel transmitters and receivers. Meanwhile, due to the highly stochastic nature of wireless channels, the propagation environments remain unlikely amenable to control. However, such randomness causes severe signal fluctuation and uncontrollable interference attributed to signals scattering, reflection, and diffraction, rendering it a critical limiting factor in the design of future wireless networks. In light of this, academic and industrial efforts have been initiated in order to explore the potentials of 6G wireless networks, which are envisioned to enable two main principles, namely, softwarization and virtualization, with the aim to conceptualize smart and adaptive radio environment paradigms [5]. In smart radio scenarios, the propagation environment are anticipated to be aware of the undergoing signals transmission, enabling self-optimization and adaptation functionalities.

With the revolutionary solid-state progression and the visualization of software-defined networks (SDNs), RISs, a.k.a intelligent reflective surfaces, have recently
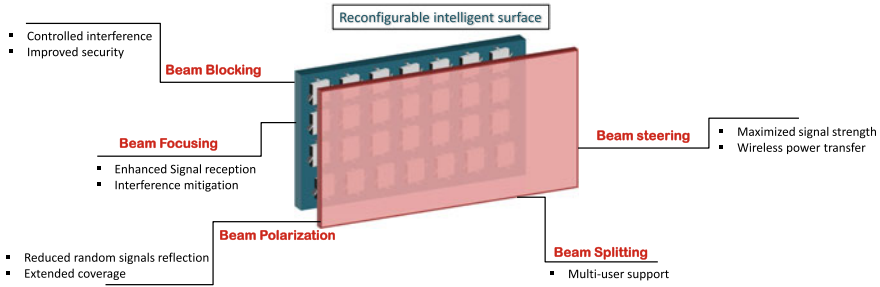
Fig. 1 Enabled functionalities by an RIS

emerged as a disruptive energy and spectrally efficient technology and an appealing candidate for 6G wireless networks [6–8]. In particular, RIS has been promoted as an innovative paradigm that is capable of offering a programmable control over the wireless propagation environment. Such features can be realized by employing an array of reconfigurable elements, referred as Metasurfaces, which enjoy unique electromagnetic (EM) properties, allowing them to enable desirable reactions when interacting with incident wireless signals. Specifically, based on the system requirements, the RIS can enable a number of engineered functionalities, including beam focusing, absorption, imaging, scattering, and polarization [9], as depicted in Fig. 1. These functionalities can be exploited to achieve particular network goals. For example, beam splitting can be utilized to enable multi-user support, while beam blocking can assist with enhancing the security and maintaining a controlled level of interference. Furthermore, beam focusing and steering can play a role in enhancing the received signal strength, mitigating interference, and enabling wireless power transfer. Extended coverage and controlled random signals reflection can be achieved by beam polarization functionality. Owing to these proactive features, RIS has become an attractive point of interest, which, according to research, can offer the following advantages. (i) Simple and flexible deployment, due to the exploitation of near-passive elements and given the fact that these smart surfaces can be mounted on building facades, aerial platforms, vehicles, etc. (ii) Spectral efficiency, (iii) energy efficiency, and (iv) compatibility [10].

3.1 Metasurfaces: The Building Block of Intelligent Surfaces

While signals reflection through a regular reflective surface follows Snell's law, the key principle of RIS follows the generalized Snell's law, where the angles of reflection do not necessarily match the angles of arrival. Rather, an RIS manipulates the incident signal phase in order to direct/split/polarize/focus the impinging signal into a desired direction with an adjusted amplitude [6]. Such alteration in the EM properties of wireless signals establishes a novel link between the physical dimension and the digital

world, rendering RIS an attractive technology for future wireless communications. In the following, we detail the fundamentals that enable such intelligent surfaces to manipulate the wireless signals in a man-made manner. Reconfigurable intelligent surfaces are made of a number of metasurfaces, which enjoy sub-wavelength thickness and can potentially function over a wide range of frequencies, spanning from the microwave band to the visible light [11]. A metasurface is regarded as a two-dimensional artificially structured array of metallic or dielectric substrates, enabling them to exhibit unique EM behavior, at the macroscopic level, and therefore, transform the impinging EM signals in various ways [5]. In particular, the RIS interaction with the incident EM waves relies on the design of the meta-atoms (which are the basis of metasurfaces), as well as the arrangement of the substrates, in which they can be organized in patches, strips, or crosses. In more details, meta-atoms experience customized and featured permittivity and permeability characteristics, that are not observed in materials found in the nature. Meta-atoms can be classified into static and dynamic designs, where the latter is equipped with an external switching element. Note that even with a simple ON/OFF switches, dynamic meta-atoms architecture is still capable of enabling an attractive range of functions. In general, the response of the meta-atoms is determined based on the inducted current when an EM wave arrives at the metasurface. In a static architecture, the resultant current pattern at the metasurface is defined by the meta-atoms geometry and composition. Similar factors affect the current patterns in dynamic architectures, in addition to the switches states [12]. Therefore, a more adaptive and fully controllable metasurface can be realized by the dynamic design of the meta-atoms, which can be achieved by properly adjusting the switches, in order to manipulate the meta-atoms permittivity and permeability, and hence, achieve the required macroscopic EM behavior [12].

3.2   RIS Versus Relaying Systems

Generally speaking, RIS can be regarded as an enhanced AF relay, in which power amplifiers are eliminated, and therefore, incident signals can be amplified/adjusted without consuming high energy, rather, by employing a large number of REs. In particular, from an energy efficiency perspective, it was proven that RIS can act as a full-duplex multiple-input multiple-output (MIMO) relay, whereas from the spectral efficiency angle, the performance of RIS is comparable with a half-duplex relay. However, self-interference experienced in full-duplex relays does not exist in the RIS, rendering RIS as an energy efficient alternative to relaying networks [13]. On a different note, by recalling that RISs comprise passive or semi-passive elements, RIS enjoys higher deployment flexibility, compared to relaying networks. Furthermore, it was demonstrated that, under the assumption that the LoS component is unavailable, the RIS outperforms AF relays, in terms of average signal-to-noise ratio (SNR), outage probability, and ergodic capacity, even when employing a few number of REs [14]. Nevertheless, with respect to average error rate, the performance of an RIS and AF relay was shown to be comparable, when employing a single RE. For a significant

enhancement to the system reliability, a larger number of REs can be leveraged with the aim to improve the achievable diversity order, and hence, remarkably reduce the average error rate.

On a different manner, it was revealed that a decode-and-forward (DF) relay would require less transmission power in order to achieve low rate, compared to an RIS. This is particularly observed when the RIS has a low number of REs [15]. Yet, as the number of REs increases and the receiver becomes closer to the transmitter or the RIS, the required transmit power for RIS-enabled networks becomes comparable to the DF relay scenario. On the other hand, in order to achieve higher rates when the transmitter-receiver distance is short, the DF relay consumes higher energy, compared to an RIS. Therefore, it can be concluded that for the case of a DF relay, the key is the number of reconfigurable elements. In specific, an RIS can outperform a DF relay when hundreds of reconfigurable elements are employed. In this regard, it is worth highlighting that, even with hundreds of elements, the RIS will be physically small, given that each element has a sub-wavelength size [15].

3.3 Path Loss Modeling in RIS-Enabled Systems

The utilization of RIS is particularly appealing for the cases when direct links between transmitters and receivers are blocked or weak. Therefore, the employment of a RIS introduces a reliable link to support and strengthen direct transmissions or to establish a reliable communication when the direct link is unavailable.

Recent research studies have demonstrated that large-scale fading in RIS-assisted networks can be modeled as free-space path-loss, in which the effect of scattering, reflection, and shadowing are neglected [10], and under the assumption that the RIS is either electrically large or small, i.e., the size of the RIS with respect to the wavelength [16–18]. In particular, the proposed models in the literature are intended to capture the relationship between the path-loss and the RIS size and distance from the transmit/receive nodes. In the following, we present the path-loss model of two scenarios, namely, near-field and far-field. Note that near-field scenario represents the case when the RIS is close to both the transmitter and receiver, or its dimensions are relatively large, i.e., width and length are 10 times larger than the wavelength (λ). On the other hand, far-field denotes a small RIS scenario, or when both the transmitter and receiver or one of them is far from the RIS. Hence, assuming W and L denote the width and the length of an RIS comprises N REs, the nth end-to-end path-loss for a near-field scenario, with respect to the RIS dimensions, can be given by [18]

$$PL_{\text{near}} = \sqrt{G_t G_r} \left(\frac{\lambda}{4\pi d_0} \right) \left[\left(\frac{d_0}{d_{\text{tr}}} \right)^{\frac{\alpha}{2}} + \left(\frac{d_0}{d_{\text{tn}} + d_{\text{nr}}} \right)^{\frac{\alpha}{2}} \rho_n \exp\left[-j \left(\theta_i + \theta_r \right) \right] \right] \quad (1)$$

where G_t and G_r denote the transmit and receive antennas gains, and d_0 and α account for the reference distance and path-loss exponent, respectively. Also, d_{tr}, d_{tn} and d_{nr} represent the transmitter-receiver, transmitter-nth RE and nth RE-receiver distances, respectively. The nth RE response is represented by the gain ρ_n, while the incident and reflection angles are given by θ_i and θ_r, respectively. Assuming perfect signal reflection with ideal phase-shift, the nth RE reflection gain can be normalized to unity, i.e., $\rho_n = 1$, while the nth phase-shift can be set to zero, $\theta_i + \theta_r = 0$. Note that for the near-field scenario, the RIS acts as an anomalous reflector, and therefore, the path-loss is affected by the summation of the traveling distances of the two links. On the other hand, for the the far-field scenario, in which each RE acts as a scatterer, the end-to-end path-loss is affected by the cascaded distances over the two links. The far-field path-loss through the nth RE can be modeled as the following

$$PL_{\text{far}} = \sqrt{G_t G_r} \left(\frac{\lambda}{4\pi d_0} \right)^2 d_0^\alpha \left(\frac{\rho_n \exp\left[-j \left(\theta_i + \theta_r + \phi_n \right) \right]}{(d_{\text{tn}} d_{\text{nr}})^{\alpha/2}} \right) \tag{2}$$

where ϕ_n denotes the adjusted phase-shift at the nth RE.

3GPP Path-Loss Model In RIS-assisted wireless networks, the RIS can be placed at the building facades, advertisement signs, traffic signals, etc. Therefore, in the following, we present the 3GPP path-loss model of RIS-assisted wireless transmission in urban environments. The total path-loss experienced over the BS-RIS link can be evaluated as the following [19]

$$PL_{\text{i-j}} = \mathcal{P}^{\text{LoS}} PL_{i-j}^{\text{LoS}} + (1 - \mathcal{P}^{\text{LoS}}) PL_{i-j}^{\text{NLoS}}, \tag{3}$$

where $\mathcal{P}^{\text{LoS}}$ is the LoS probability, PL_{i-j}^{LoS} and PL_{i-j}^{NLoS} are the associated losses in the LoS and NLoS conditions between communicating devices i and j, such that $(i, j) \in \{(\text{BS,RIS})\}$.

Assuming that the RIS devices equipping the building are installed below $23\,\text{m}$ (i.e., up to 7 floors buildings), the LoS probability between devices i and j can be expressed by [19, Table 7.4.2-1]

$$\mathcal{P}^{\text{LoS}} = \begin{cases} 1 & \text{if } d_{\text{i-j}}^{2D} \leq 18\,\text{m} \\ \left(\frac{18}{d_{i-j}^{2D}} + \exp\left(-\frac{d_{i-j}^{2D}}{63} \right) \left(1 - \frac{18}{d_{i-j}^{2D}} \right) \right) \\ \times \left(1 + f(h_j) \frac{5}{4} \left(\frac{d_{i-j}^{2D}}{100} \right)^3 \exp\left(-\frac{d_{i-j}^{2D}}{150} \right) \right) & \text{if } d_{\text{i-j}}^{2D} > 18\,\text{m}, \end{cases} \tag{4}$$

where d_{i-j}^{2D} is the 2D separating distance (projected on the ground) between devices i and j in m, $(i, j) \in \{(\text{BS,RIS})\}$, and $f(h_j)$ is given by

$$f(h_j) = \begin{cases} 0 & \text{if } h_j \leq 13\,\text{m} \\ \left(\frac{h_j - 13}{10}\right)^{1.5} & \text{if } 13\,\text{m} < h_j \leq 23\,\text{m}, \end{cases} \quad (5)$$

while the path-loss for LoS and NLoS communication links are written by [19, Table 7.4.1-1]:

$$PL^{\text{LoS}} = 28 + 22\log(d_{i-j}) + 20\log(f) + X \quad (6)$$

and

$$PL^{\text{NLoS}} = \max\left(PL^{\text{LoS}}, \bar{PL}^{\text{NLoS}}\right) \quad (7)$$

where

$$\bar{PL}^{\text{NLoS}} = 13.54 + 39.08\log(d_{i-j}) + 20\log(f) - 0.6\,(h_j - 1.5) + X, \quad (8)$$

d_{i-j} is the 3D distance between devices i and j in m, f is the carrier frequency in GHz, and h_j is the RIS altitude (measured from the middle point for RIS). Also, X represents a log-normal random variable denoting the shadow fading, with standard deviation equals to $\sigma = 4$ dB and $\sigma = 7.8$ dB for LoS and NLoS, respectively.

Finally, assuming that the UAV flying altitude is regulated under 150 m, the link between the RIS and the UAV can be represented by the air-to-ground 3GPP model [20]

$$PL_{\text{RIS–UAV}} = 28 + 22\log_{10}(d_{\text{RIS–UAV}}) + 20\log_{10}(f) + X_{\text{UAV}}, \quad (9)$$

where X_{UAV} is the normally distributed shadow fading with deviation $\sigma = 4.64\,e^{-0.0066\,h_{\text{UAV}}}$ in the urban environment.

4 Integration of RIS into UAV Networks: A Review

As studied in [8], RIS is capable of improving the received SNR and the latter increases quadratically when the number of RIS reflecting elements doubles. Such interesting performances, combined with the small payload of RIS compared to active communication equipment has motivated the integration of RIS in aerial platforms, in particular with UAVs. This integration can be identified in two types: First, RIS-assisted UAVs, where RIS mounted on objects, such as buildings facades, vehicle roofs, and towers, can be used to assist UAVs to sustain their beyond visible LoS (BVLoS) communications, i.e., UAVs are controlled without a direct command and control (C&C) link between the pilot and the UAV, to bypass obstacles in their communications with ground users/devices, or to secure such communication links [21–23]. Second, A UAV can be equipped with an RIS in order to reduce on-board payload and save battery usage, while providing efficient communications to ground devices [18, 24–26]. These types are further explained below.

4.1   RIS-Assisted UAV Systems

Assisting UAV communications through RIS has received a lot of attention recently. In [21], the authors investigated the joint problem of UAV trajectory and RIS's passive beamforming design aiming to maximize the average received data rate at a ground user served through the RIS and UAV in a multi-hop fashion. As in [21], the authors of [27] focused on UAV trajectory design and phase shifts optimization, targeting to maximize the sum data rate of a group of ground users. Due to the non-convexity of the problem, an alternating optimization (AO) method, which decomposes the problem into two sub-problems, is developed. Given optimal phase shifting, UAV trajectory design is solved using the successive convex approximation method. Results validate the superiority of the proposed approach compared to benchmarks. Moreover, Yang et al. studied in [22] a similar system, where they derived the analytical expressions of outage probability and average bit error rate (BER). Obtained results demonstrate the advantageous use of the RIS to improve the coverage and reliability of the UAV communication system. Also, authors of [28] extended the previous works to the use of multiple RIS devices and in the mmWave frequency band. Given predefined UAV flying trajectory and minimum QoS requirements, they jointly optimized the deployment, user scheduling, and phase shifting of RIS. An AO-based approach is developed, which is shown to provide superior sum data rate performance than deployments without RIS/UAV optimization. In addition to communication purposes, RIS can be used to assist mobile edge computing (MEC) services in the sky, i.e., by allowing MEC-enabled UAVs to provide computation to ground users through the RIS. In that matter, Mei et al. investigated in [29] the related problem of joint UAV-trajectory, task/cache design, and phase shifts optimization, aiming to maximize the energy-efficiency of the MEC system. The non-convex problem is solved using a sub-optimal successive convex approximation (SCA), and numerical results showed a substantial performance increase compared to benchmarks. Liu et al. developed in [30] an RIS/UAV integration framework, where RIS is deployed to assist a UAV in serving ground users through the non-orthogonal multiple access (NOMA) scheme. Energy minimization problem was formulated, where UAV trajectory, RIS phase shifting, and NOMA power allocation are jointly optimized. Due the non-convexity of the problem, the authors proposed a reinforcement learning solution, based on decaying deep-Q-network. Through simulations, they demonstrated that their method converges faster that conventional Q-learning. Also, UAV's energy consumption is significantly reduced by integrating RIS into the system. Finally, dynamically optimizing the NOMA decoding order and power allocation allows to decrease energy consumption by 11.7% compare to the benchmark without NOMA. Finally, from the security perspective, Li et al. investigated in [23] the maximization of the average worst-case secrecy rate, defined as the difference in data rates between the communication of a legitimate user and that of an eavesdropper. The authors studied the joint design of the UAV trajectory, RIS phase shifting, and transmit powers of legitimate ground users. Due to the non-convexity of this problem, an AO approach is proposed, where three sub-problems

were formulated and solved using the SCA, $\mathcal{S}$-Procedure, and semi-definite relaxation (SDR), respectively. Obtained results confirmed the robustness of the proposed solution, and showed its significant average secrecy rate gain compared to baseline algorithms. These works are summarized in Table 1.

4.2 RIS-Equipped UAV Systems

The idea of equipping UAVs with RIS, called RIS-UAV, is mainly driven by the UAV motion flexibility to establish strong LoS links with ground devices, thus saving transmit power. Also, due to the typically limited payload and power of UAVs, which may not be able to carry and operate efficiently heavy radio-frequency (RF) transceivers, using RIS instead allows to reduce energy costs. This vision has been first proposed in [25] where it was demonstrated that an RIS-UAV can extend the coverage area of terrestrial BSs, thus filling the coverage holes and meeting users' high-speed broadband needs. In such scenarios, a ground control station is responsible for sending the required configurations allowing the onboard RIS controller to configure RIS phase shifts and direct signals towards the targeted receivers. The same authors conducted in [18] a rigorous link budget analysis for RIS-mounted aerial platforms, including UAVs, high-altitude platforms (HAPS), and low-earth orbit (LEO) satellites. Their results draw insights and guidelines about the use of RIS in aerial platforms. Specifically, it was shown that (1) the RIS-UAV performance is independent from the operating frequency when maximal number of REs is used, (2) with high receiver antenna gain, RIS-UAV data rate is close to that of other platforms, and (3) best data rates are achieved when the RIS-UAV is close to the ground transmitter or receiver. The RIS-UAV vision has been further studied in [31, 32], where novel use cases, challenges, and opportunities were identified and explained. In [26], the authors used the RIS-UAV to maximize cellular coverage within a geographical area. Specifically, they jointly optimize RIS-UAV phase shifting and BS beamforming problem, aiming to maximize the worst received SNR, while taking into account practical flight effects, i.e., undesired RIS-UAV oscillations due to adverse atmospheric conditions. Results proved the robustness and reliability of the flight effects combating method, and its gain of about 25 dB over state-of-the-art schemes. Finally, regarding such systems' security, the authors of [24] proposed to use an RIS-UAV to secure the uplink communications between ground users and a BS. They focused on maximizing the secrecy energy efficiency, defined as the ratio of the secrecy rate and consumed power, through the joint optimization of UAV trajectory, RIS phase shifting, user association, and transmit power. The problem is tackled with an AO-based approach, then, simpler schemes were proposed to solve the RIS phase shifting and UAV trajectory sub-problems. Simulation results illustrated the fast convergence of the proposed method, and the improvement in the secrecy energy efficiency by up to 38% compared to schemes without RIS. Alternatively, RIS has been used in [33] to mitigate jamming signals by accurately optimizing the phase shifts and RIS-UAV location. The aforementioned works are summarized in Table 2.

Table 1 Related works (RIS-assisted UAV systems)

References	Focus	Objective	Findings
[21]	Joint UAV trajectory and RIS phase-shift design	Max. avg. achievable rate	– Locally optimal solution obtained using SCA – Proposed algorithm increases avg. achievable rate compared to heuristic benchmarks
[27]	Joint UAV trajectory and RIS phase-shift design	Max. sum data rate of ground users	– Optimal solution obtained using AO – RIS enhances the quality of UAV communications – Proposed approach outperforms heuristic UAV trajectory designs
[22]	Analytical modeling of RIS-assisted UAV communication links	Derivation of outage probability and avg. BER expressions	– RIS improves coverage probability, avg. capacity, and system reliability
[28]	Joint optimization of multiple RIS deployment, user scheduling, and phase shifting	Max. sum data rate of ground users	– Sub-optimal solution obtained using AO – Proposed solution is superior to benchmarks without RIS phase-shifting and/or UAV trajectory optimization
[29]	Joint UAV trajectory, task/cache placement, and RIS phase shift design	Max. energy efficiency of RIS-assisted MEC-enabled UAV system	– Sub-optimal solution obtained using SCA – Proposed solution is superior to static cache/task placement and non-optimized RIS designs
[30]	Joint optimization of UAV trajectory, RIS phase shifts, and NOMA power	Min. energy consumption of RIS-assisted UAV NOMA downlink	– A reinforcement learning based solution is developed – Dynamic optimization of NOMA order/power reduces energy consumption compared to non NOMA benchmarks
[23]	Joint design of UAV trajectory, RIS phase shifts, and legitimate users' transmit power	Max. avg. secrecy rate	– Sub-optimal solution obtained using AO – Proposed approach is robust against channel uncertainties and outperforms heuristic baselines

Table 2 Related works (RIS-equipped UAV systems)

References	Focus	Objective	Findings
[25]	Control architecture design and case studies of RSS-equipped aerial platforms	Extend coverage of terrestrial BSs	– Proposed control architecture is viable – With a fixed number of reflectors, the UAV achieves the best receive power performance
[18]	Link budget analysis of RIS-equipped UAV communication links	Derivation of receive power expressions and maximal achievable data rates	– RIS-equipped UAV performance is independent from the operating frequency – With high receive antenna gain, RIS-equipped UAV's data rate is close to that of other platforms – The best performance is obtained when the RIS-equipped UAV is close to the ground transmitter or receiver
[31, 32]	Case studies and challenges discussion of RIS-equipped UAV systems	Shedding light on potential uses and opportunities of RIS-equipped UAV systems	– Overview of applications enabled by RIS-equipped UAV systems – Introduction of research, implementation, and experimentation guidelines for RIS-equipped UAV systems
[26]	Joint optimization of BS beamforming and RIS phase shifting	Max. worst received SNR	– Proposed approach is guarantees robust coverage against UAV oscillations and outperforms the agnostic benchmark
[24]	Joint optimization of UAV trajectory, RIS phase shifts, user association, and transmit power	Max. secrecy energy efficiency	– Sub-optimal solution obtained using AO – Proposed method converges fast and is superior by 38% to non-RIS baselines
[33]	Joint optimization of UAV location and RIS phase shifts	Max. legitimate user data rate	– An AO-based solution is proposed – Proposed method effectively compensates jamming and outperforms the non-RIS benchmark

4.3 Use Cases and Performance Evaluation

Clearly, RIS-assisted and RIS-equipped UAV communications have a significant potential use in public safety networks. For instance, by relying on the RIS over building facades or other objects, and on the motion flexibility of UAVs, FR communications can benefit from frequent LoS links, and thus sustain communications while dealing with emergency situations. Moreover, in a hard-to-reach area, the concurrent use of dedicated emergency communication channels from the closest BS combined with an accurate deployment of an RIS-UAV enables temporary communication/computing services for the time to deal with the emergency. Such a deployment can be punctual, recurrent, or periodic in order to ensure surveillance of critical assets.

In order to acquire an understanding about the potential use of RIS-assisted and RIS-mounted UAV systems, we present below public safety use cases with their corresponding link budget analysis and performances.

RIS-Assisted UAV Systems Assisting UAVs with RIS is an interesting feature that would allow extended coverage, higher capacity, and flexible spectrum sharing, for public safety services such as search and rescue, disaster response, and surveillance. For instance, by relying on multiple RIS devices along the path separating the BS from the controlled UAV, the action area of the latter can be significantly increased, which allows for fast and efficient response to threatening incidents within the covered region.

In line with the aforementioned example, we consider a UAV deployed for surveillance purposes in a predefined region. Due to the lack of cellular coverage due to blockages or weak signals, we assume that K RIS devices are deployed in the area to strengthen signals incoming from a BS in a multi-hop fashion, i.e., the BS's signals are forwarded among RIS devices until they reach the UAV, as depicted in Fig. 2. Also, we assume that the RIS devices are numbered from 1 to K, such that RIS_1 is the closest to the BS, while RIS_K is the closest to the UAV, and that RIS k is equipped with N_k reflecting elements, $k = 1, \ldots, K$. In terrestrial environments, an RIS is typically installed on a facade of a building, mainly in an urban environment. Subsequently, the 3GPP model presented in (3)–(5) can be used to model path-loss. Given that in this section we consider K RISs, nodes i and j are set such that $(i, j) \in \{(\text{BS},\text{RIS}_1),$ $(\text{RIS}_k,\text{RIS}_{k+1})\}; k = 1, \ldots, K - 1\}$.

Subsequently, assuming perfect phase shifting, the link budget of the RIS-assisted UAV communication can be given by

$$P_r = P_t + G_t + G_r - PL_{\text{BS}-\text{RIS}_1} - \sum_{k=1}^{K-1} PL_{\text{RIS}_k-\text{RIS}_{k+1}} - PL_{RIS_K-UAV}$$
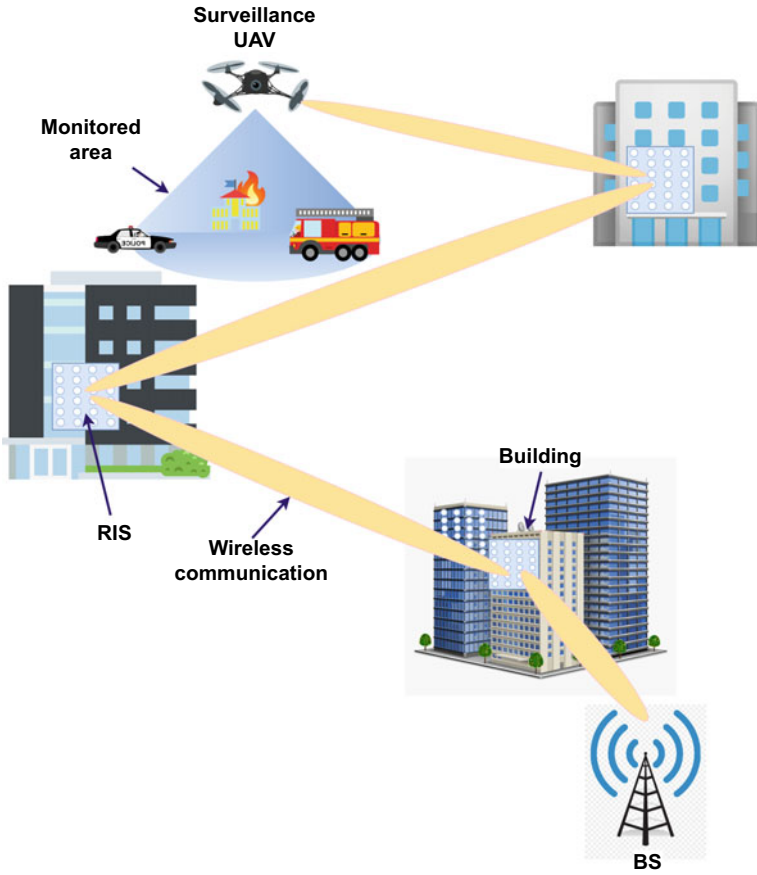$$+20\sum_{k=1}^{K} \log{(N_k)}, \quad (10)$$

Fig. 2 RIS-assisted UAV communication for surveillance

where P_r is the received power at UAV, P_t is the transmit power of the BS, and G_t and G_r are the transmit and receive gains of the BS and UAV respectively.

The related data rate can be expressed by

$$R = B \log_2 \left(1 + \frac{P_r}{P_n} \right), \tag{11}$$

where B is the transmission bandwidth and P_n is the noise power, defined as

$$P_N = kTBF, \tag{12}$$

where $k = 1.38 \times 10^{-23} \text{J.}^\circ\text{K}^{-1}$ is the Boltzmann constant, T is the temperature in $^\circ$K, and F is the noise figure.
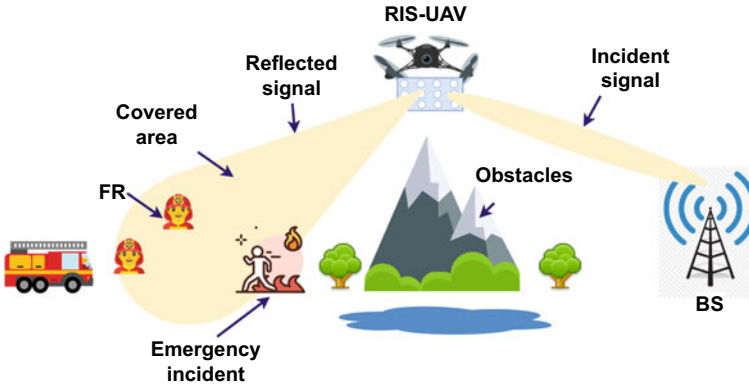
Fig. 3 RIS-UAV assisted communication for search and rescue

RIS-Equipped UAV Systems Unlike the previous use case, an RIS can be mounted on a UAV, thus providing more placement flexibility, which is expected to improve communications' quality of service. Assuming a search and rescue where FR teams (FRs) have to reach an endangered area where victims have been located, RIS-UAVs can be deployed over selected areas to provide connectivity to ground teams. For the sake of simplicity, we consider that a BS communicates with the FR in the targeted area via one RIS-UAV, deployed for the occasion, as illustrated in Fig. 3.

Assuming the 3GPP air-to-ground channel model, it is plausible to assume that communication links are all in LoS. Hence, path-loss in rural and urban environments can be expressed by [20]

$$PL_{\text{BS−UAV}}^{\text{rural}} = \max\left(23.9 - 1.8\log_{10}(h_{\text{UAV}}), 20\right)\log_{10}(d_{\text{BS−UAV}})$$
$$+20\log_{10}(\frac{40\pi f}{3}) + X_{\text{UAV}}, \qquad (13)$$

$$PL_{\text{UAV−FR}}^{\text{rural}} = \max\left(23.9 - 1.8\log_{10}(h_{\text{FR}}), 20\right)\log_{10}(d_{\text{UAV−FR}})$$
$$+20\log_{10}(\frac{40\pi f}{3}) + X_{\text{FR}}, \qquad (14)$$

$$PL_{\text{BS−UAV}}^{\text{urban}} = 28 + 22\log_{10}(d_{\text{BS−UAV}}) + 20\log_{10}(f) + X_{\text{UAV}}, \qquad (15)$$

and
$$PL_{\text{UAV−FR}}^{\text{urban}} = 28 + 22\log_{10}(d_{\text{UAV−FR}}) + 20\log_{10}(f) + X_{\text{FR}}, \qquad (16)$$

where h_i, d_{i-j}, and X_{UAV} are defined as in the previous subsection, while X_{j} is the normally distributed shadow fading with deviation as in (8) for the urban environment and with deviation $\sigma = 4.2\, e^{-0.0046\, h_{\text{j}}}$ for the rural environment.

Fig. 4 Impact of the
location of the RIS on the
data rate ($K = 1$)
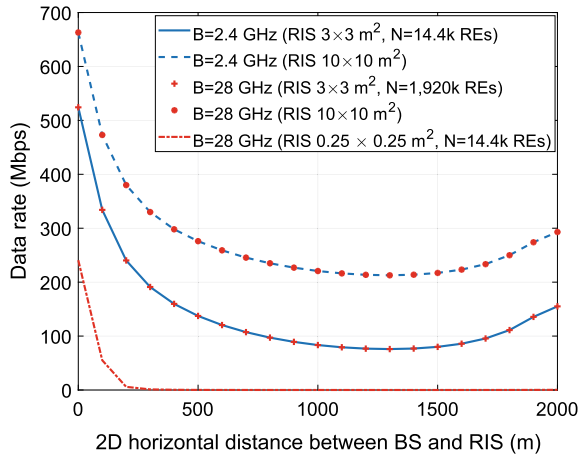
Given ideal phase shifting, the link budget of the RIS-UAV assisted communication can be given by [18]

$$P_r^k = P_t + G_t + G_r - PL_{BS-UAV}^k - PL_{UAV-FR}^k + 20 \log (N), \ k \in \{\text{rural, urban}\} \tag{17}$$

where P_r^k is the received power at FR in the urban or rural environment. Finally, the data rate can be expressed using (11).

Performance Evaluation We evaluate here the achieved data rate performance for the described use cases above, where the impact of key parameters is also investigated.

For the first use case (RIS-assisted UAV surveillance), we assume that the system parameters are set as follows: The altitudes of the BS, RIS devices on buildings' facades, and UAV are set to $h_{BS} = 25$ m, $h_{RIS_k} = 10$ m, $\forall k = 1, \ldots, K$, and $h_{UAV} = 100$ m, respectively. Also, the transmit power of the BS is $P_t = 35$ dBm, the transmit and receive gains $G_t = 8$ dBi, and $G_r = 5$ dBi, the frequency $f = 2.4$ GHz, and the bandwidth $B = 20$ MHz [19]. Finally, the area of RIS devices is $A_k = 3 \times 3$ m^2, $\forall k = 1, \ldots, K$ and the number of hosted reflecting elements in the RIS is calculated by [18]

$$N_k = \frac{A_k f^2}{(0.2v)^2}, \forall k = 1, \ldots, K, \tag{18}$$

where $v = 3 \times 10^8$ m/s is the speed of light, and 0.2 is the minimal separation between reflecting elements, considering the scattering paradigm [18].

In Fig. 4, given $K = 1$, we depict the data rate performance as a function of the 2D distance between the BS and RIS. As it can be seen, the best performance is achieved when the RIS is the closest to the BS. When the RIS is located about halfway from the UAV, the performance is the lowest due to the degraded incident and reflected signals through the RIS. However, when the RIS is close to the UAV, the data rate slightly increases. This is due to the improved quality of the RIS-UAV channel.

Fig. 5 Impact of the number
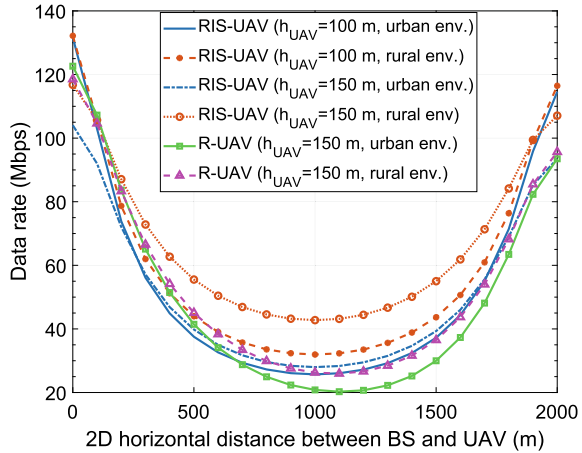of RIS devices on the data
rate
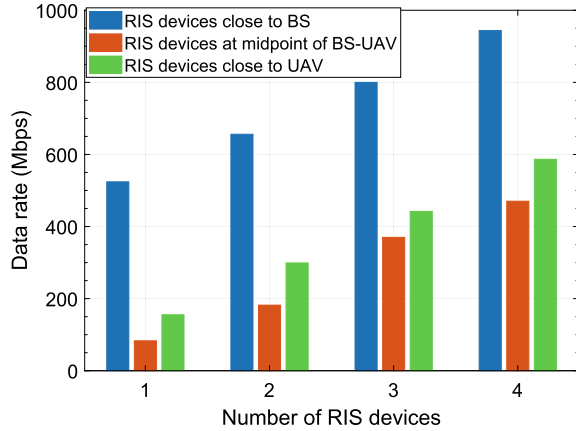
Also, we notice that the performance is insensitive to the used frequency band, for the same RIS area. For instance, given RIS with $A = 9\,\text{m}^2$ and $f = 2.4\,\text{GHz}$, the RIS is equipped with $N = 14.4\text{k}$ reflecting elements according to (18), while $N = 1,960\text{k}$ reflecting elements for $B = 28\,\text{GHz}$ within the same RIS area. It means that the RIS compensates the use of a higher frequency band, which degrades the transmission performance, by the deployment of a larger number of reflecting elements. Finally, when the same number of reflecting elements is used for different frequencies, we found that the higher the frequency, the worst is the data rate performance. This is expected since higher frequencies experience significant environment attenuation, which reduces its efficacy.

Clearly, assisting UAVs in their operation with high data rates would require the use of a sufficiently large RIS regardless of the operating frequency. Nevertheless, the best performances are obtained when placing the RIS closer to the BS.

Figure 5 shows the performance of the multi-hop system, where several RIS devices are used to forward the signals from the BS to the UAV. We distinguish three different cases, where each one corresponds to clustered RIS devices close to either the BS, the middle point between BS-UAV, or close to the UAV. First, we see that forwarding signals in a multi-hop fashion does improve significantly the data rate, conditioned on the same distribution of RIS devices. However, if the RIS locations are inadequate, one would strategically forward the signal through a single or at most two optimally located RIS devices in order to enhance the data rate. Finally, the best performance is achieved for RIS devices close to the BS, which agrees with the results of the previous Figure. Consequently, it is recommended to have RIS devices deployed on the facades of buildings close to the BS, which allows to bypass blockages within the surroundings.

For the second use case (RIS-UAV search and rescue), we consider the following parameters values: Altitudes of BS, RIS-UAV, and FR are set to $h_{BS} = 25$ m, $h_{RIS-UAV} = 100$ m or 150 m, and $h_{FR} = 1.5$ m, respectively. Also, the transmit power, transmit and receive gains, frequency, and bandwidth are set exactly as in

Fig. 6 Impact of the
location of the RIS-UAV on
the data rate

the previous use case. Finally, the area of the RIS device mounted on the RIS-UAV
is $A_{RIS-UAV} = 0.25 \times 0.25$ m², thus the number of hosted reflecting elements is
$N_{RIS-UAV} = 100$ [18].

In Fig. 6, we present the data rate performance as a function of the 2D distance
between the BS and RIS-UAV, and for different RIS-UAV altitudes. Moreover, we
compare the proposed RIS-UAV system to the conventional amplify-and-forward
UAV relay, denoted R-UAV [34]. Clearly, the best performance is achieved when the
UAV (either RIS-UAV or R-UAV) is the closest to the BS, while the worst is obtained
at or close to) the midpoint between the BS and FR. When the RIS-UAV is close to
the FR, the data rate enhances significantly, but remains at a lower level than in the
case of RIS-UAV close to the BS. Also, for the same RIS-UAV altitude, the achieved
data rate is better in the rural environment than in the urban one. This is mainly due
to stronger communication links with better LoS conditions, which strengthens the
received signal at the FR. However, for the same environment conditions, the RIS-
UAV altitude has an important impact on the performance. Specifically, we notice that
a lower $h_{RIS-UAV}$ achieves better performances when deployed close to the BS or to
the FR. In contrast, a higher altitude provides better data rates when the RIS-UAV is
located somewhere between the BS and the FR. Indeed, a higher altitude would favor
more LoS links, which compensates for the degraded communications to/from the
RIS-UAV when located in-between the BS and FR. Clearly, as a RIS-UAV would be
deployed and handled by the FR team on the ground, it is more likely that it would
achieve a satisfying data rate. Nevertheless, a careful altitude optimization would
be needed to obtain the best performance When compared to the R-UAV system at
$h_{UAV} = 150$ m, we notice that in the rural environment the RIS-UAV and R-UAV
performances are almost the same for a UAV placed very close to the BS (under
100 m), while RIS-UAV outperforms R-UAV when the UAV is placed farther. In the
urban environment, RIS-UAV is superior to R-UAV only when it is away from the BS

by at least 650 m. We conclude that the use of RIS-UAV is mostly relevant for rural long range communications, as the case in wide areas search-and-rescue missions.

4.4 Limitations of RIS-Enabled UAV Networks

Despite the promising potentials realized when integrating RIS into UAV networks, the performance of such integration is constrained by several factors. First, although higher number of REs implies enhanced performance and improved coverage, due to the limited size of UAVs, and in order to guarantee flexible and stable flight, particularly in turbulence scenarios, several constraints are imposed on the sizes of RISs implemented on UAVs. Furthermore, the relatively high mobility and wobbling effect of UAVs requires frequent channel state information (CSI) acquisition and, hence, continuous RIS reconfiguration. Therefore, an increased overhead is resulted, imposing new challenges on the deployment of on-demand and fast RIS-enabled UAV communications in public safety networks. Moreover, joint trajectory design and resource allocation optimization represents a challenging factor in the implementation of RIS-enabled UAVs for public safety networks. Specifically, the joint optimization is required to ensure maximized coverage while maintaining high energy efficiency, in order to meet the needs of public safety networks under the limitations imposed by the constrained UAV capabilities.

5   Challenges and Future Directions

In this section, we outline the main challenges and the associated potential future research opportunities, with the aim to pave the way for the successful realization of efficient public safety networks thorough the utilization of RIS-enabled UAVs.

– **RIS response optimization:** Given that UAVs hover at relatively high speeds, this necessitates more frequent CSI acquisition, and subsequently, an increased number of RIS re-configuration rounds. These extensive operations introduce additional signaling overhead on the flying UAVs, in order to achieve the optimum RIS configuration, and therefore, efficiently accomplish the assigned missions pertaining to emergency cases in public safety networks. This calls for the design of reliable CSI estimation and RIS configuration in RIS-empowered UAVs for public safety networks.
– **Constrained RIS size in RIS-equipped UAVs:** In order to leverage the flight flexibility, as well as to maintain a stable UAV motion, the size of an RIS mounted on a UAV is limited by several constraints. Such constraints might have direct impact on the performance of the RIS, and can potentially limit the functionalities applied by the RIS. This is particularly pronounced when the UAVs are experienc-

ing turbulence. This constraint can be loosen for RIS-assisted UAVs, depending on the considered use case and the underlying system model.

– **Channel Modeling:** Although large-scale and small-scale channel modeling has been extensively tackled in the literature, and a number of authors have proposed diverse channel modeling frameworks for near-field and far-field scenarios, the available models in the literature are still lack the comprehension. In more details, most of the reported results have primarily focused on the characterization of large-scale and small-scale fading under ideal unrealistic assumptions. There is still a compelling need for a comprehensive framework to demonstrate the RIS-enabled UAV channel models under practical scenarios, including high mobility as well as UAV wobbling. It should be highlighted that UAV wobbling constitute a major challenge on the design of accurate channel models, as it has a high impact on the quality of the UAV-RIS links, rendering channel modeling for RIS-enabled UAVs an open research topic.

– **Incorporating Machine Learning Algorithms:** It is foreseen that the integration of RIS and UAV networks for the sake of accomplishing resilient public safety communication would necessitate a sophisticated level of organization, in order to coordinate the UAV trajectory, flying time, energy consumption, as well as optimizing the RIS configuration. In this regard, machine learning is deemed as an enabler for such networks, in which advanced machine learning algorithms can be developed and utilized in order to orchestrate the operation in RIS-enabled UAVs for public safety network. It is worth highlighting that such topic is barely touched in the literature, hence, it represents a potential future research direction.

– **Physical Layer Security of Public Safety Communications** As the significance of the physical layer security (PLS) is more pronounced in highly dynamic networks, such as UAV networks, it is essential to develop enhanced PLS schemes for RIS-enabled UAV networks that fulfill the security requirements of public safety networks. It is worth highlighting that public safety networks are vulnerable to several physical layer attacks, particularly jamming and spoofing attackS, which have critical impact on such networks, resulting on serious consequences, including humans death. Motivated by this, it is of paramount importance to introduce novel PLS mechanisms to ensure reliable and secure public safety communication, in the context of RIS-enabled UAVs.

– **Integration with other Non-terrestrial Networks** The emergence of the concept of integrated satellite-aerial-terrestrial (SAT) networks was inspired by the several advantages offered by such networks, including enhanced throughput, coverage, and resilience, which are key components in realizing efficient public safety communications. Yet, the adoption of integrated SAT networks introduces novel challenges pertaining to the heterogeneity and the time-variability nature of these networks. Therefore, to realize the full potential of integrated SAT networks as a key enabler for efficient public safety communication, thorough investigation should be conducted to quantify the performance of such networks, and to point out the major limitations for the development of resilient solutions.

6 Conclusion

In this chapter, we overviewed the fundamentals, design aspects, and applications of RIS as an enabling technology of future wireless services. Specifically, we studied the integration of RIS into UAV technology by focusing on RIS-assisted UAV networks and RIS-equipped UAV systems. To demonstrate their feasibility and potential, we developed two use cases related to public safety, namely aerial surveillance and search-and-rescue UAV missions. Through analysis and simulation results, we illustrated the achievable data rate performances, which validate the relevance of RIS-enabled UAV networks. Finally, we listed the current limitations of this integration and provided valuable insights about the future research directions to further develop RIS-enabled UAV systems.

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