Abstract—The high configurability and low cost of Reflective Intelligent Surfaces (RISs) made them a promising solution for enhancing the capabilities of Beyond Fifth-Generation (B5G) networks. Recent works proposed to mount RISs on Unmanned Aerial Vehicles (UAVs), combining the high network configurability provided by RIS with the mobility brought by UAVs. However, the RIS represents an additional weight that impacts the battery lifetime of the UAV. Furthermore, the practicality of the resulting link in terms of communication channel quality and security have not been assessed in detail. In this paper, we highlight all the essential features that need to be considered for the practical deployment of RIS-enabled UAVs. We are the first to show how the RIS size and its power consumption impact the UAV flight time. We then assess how the RIS size, carrier frequency, and UAV flying altitude affects the path loss. Lastly, we propose a novel particle swarm-based approach to maximize coverage and improve the confidentiality of transmissions in a cellular scenario with the support of RISs carried by UAVs.

Index Terms—Reflective Intelligent Surface, Unmanned Aerial Vehicles, Beyond 5G, Area Secrecy

I. INTRODUCTION

Massive Multiple-Input Multiple-Output (MIMO) represents the key technology employed by Beyond Fifth-Generation (B5G) wireless networks to serve billions of active wireless devices which are still increasing annually. In conjunction with Millimeter Waves (mmWaves), massive MIMO enables B5G networks to support novel uses cases, such as virtual and augmented reality, high-fidelity holographic projections, digital twins, and autonomous driving. All these scenarios can meet the large bandwidth available at higher frequencies. Although literature widely discussed applications and advantages of the mmWave technology, its widespread adoption is still limited by both its severe path-loss and its sensitivity to blockages. Despite of the good achievable rate, MIMO and mmWave require complex signal processing algorithms, are costly, and present high energy demand to support an high number of Radio Frequency chains. Ultra-Dense Network (UDN) is another paradigm that has been proposed for B5G systems. UDN technology envisions the deployment of a large number of Base Stations (BSs) that are not only expensive in terms of hardware and maintenance, but also increase the amount of interference in the network.

Reflective Intelligent Surfaces (RISs) represent a new energy-efficient technology for re-configuring the wireless propagation environment via software-controlled reflections. This technology falls under different names in the literature, such as Reconfigurable Intelligent Surface, or Intelligent Reflective Surfaces, which however represent the same type of devices. RISs improve the performance of wireless communication networks by using massive low-cost passive reflecting elements integrated on a surface, therefore eliminating the need for Radio Frequency (RF) chains. By independently controlling the amplitude and phase of each element, RISs exploit passive beamforming to either enhance the signal directivity or null signals at the receivers. Furthermore, RISs inherently enable full-duplex communications without interference, providing higher spectral efficiency than other solutions.

To fully exploit the potential of RISs, recent works focused on enhancing the flexibility of the network by moving RISs in different locations over time. Therefore, the RIS shall be mounted on movable devices with a certain automation level and able to coordinate with other devices in the network. A relevant example of such devices is given by Unmanned Aerial Vehicles (UAVs). When moving communication equipment’s operating as BSs, relays, or RISs, UAVs enhance the performance of wireless networks due to their high mobility, low cost, low power consumption, and high mobility. This framework can be exploited for several purposes, as we later discuss throughout the paper. However, using RIS-enabled UAV opens new challenges compared to regular UAVs. In fact, the RIS controller demands for power from the UAV battery, shortening its lifetime. Furthermore, the weight of the RIS requires extra thrust from the UAV to fly, further shortening the battery lifetime.

In this paper, we analyze the requirements and limits of the deployment of RIS-enabled UAVs. We first provide a characterization of RISs in terms of weight and power demand, to show how they impact on the flight performance of a UAV. Furthermore, since the flying altitude of UAVs depends on the countries’ policy, we show how the altitude impacts communications in terms of path loss incurred in the communication channel transmitter-RIS-receiver. Thanks to this characterization, we then show the performance of RIS-enabled UAVs for two different applications in cellular networks: i) maximization of the average users’ achievable rate, and ii) minimization of the network area secrecy to prevent eavesdropping by malicious users. In particular, we provide the following contributions.

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• We investigate the fundamental limits of flight time of UAVs carrying RIS. First, we derive the impact of the RISs on the UAV power consumption, which in turn significantly reduces the flight time. Hence, we conclude that it is fundamental to design proper energy harvesting schemes or use backup drones to guarantee the network’s resiliency.

• We investigate the capabilities of a RIS-enabled UAV in the context of millimeter wave communications. To optimize the spectral efficiency, we design a novel particle swarm optimization algorithm for the optimal deployment of drones and a coordinate descent algorithm to compute the optimal power allocation and RIS phase-shift configuration. By accounting for the RIS path loss modeling at those frequencies, we show how UAV’s flight altitudes imposed by real regulations in different countries and the number of RIS elements impact the network performance.

• By using the optimization strategies of the previous point, we optimize the secrecy capacity of the network in a predefined area. We investigate the impact of the UAV’s altitude and the RIS size on the network secrecy performance.

We believe our paper can serve as a reference for the design of networks exploiting RIS mounted on UAV, providing insights on both technological limitations and benefits.

II. REFLECTIVE INTELLIGENT SURFACES

In this section, we first discuss the RIS’s architecture and dimension, and then provide an overview of their power consumption.

The typical hardware architecture of a RIS is based on the concept of meta-surface, which is a planar array consisting of a large number of meta-atoms. A RIS consists of three layers and a controller. The first layer (outer layer) consists of a metallic patch of reflecting elements printed on a dielectric substrate to directly interact with the incident signals. The second layer (middle layer) is a copper plate used to avoid leakage in the signal energy. Lastly, the third layer (inner layer) is a control circuit board responsible for adjusting the reflection amplitude and phase shift of each element; this layer is triggered by a smart controller attached to the RIS. Due to their passive nature, RISs can be fabricated with limited layer thickness. Therefore, their weight is limited making them suitable to be mounted on different surfaces. A Field-Programmable Gate Array (FPGA) can operate as controller, which also helps in the communication and coordination with other network components. Phase and/or amplitude adjustment can be obtained using Positive-Intrinsic-Negative (PIN) diodes, Field-Effect Transistors (FETs), or Micro Electro Mechanical System (MEMS) switches. Each element includes a PIN diode, which can be switched ON and OFF by controlling its biasing voltage using the controller, thereby generating a phase shift. A resistor with variable load is applied to control the reflection amplitude. By changing the value of this resistor, different portions of the incident signal’s energy are dissipated, thus the reflection amplitude varies between [0, 1]. The number of elements in a RIS relatively affects amplification of signals. The size \( \lambda \) of the elements is in the order of fractions of the wavelength of the transmission carrier. Common values vary between \( \lambda/10 \) and \( \lambda/2 \) with a spacing of \( \lambda/2 \). For instance, the dimension of a 20 x 30 RIS with a 28 GHz (\( \lambda = 1 \) cm) carrier frequency is 0.2 x 0.3 m. The weight of the RIS depends on the three layers. Based on the previous discussion, the heavier layer is the copper plate, whereas the controller and reflective elements do not significantly contribute. Very few works discussed physical implementations of RISs [1], [2], [3]. We show the details of these implementations in Table I.

As previously mentioned, one of the benefits of RISs is their low energy consumption. The total power consumption of the RIS at a certain time instant depends on the number of active elements (i.e., the number of diodes in the ON state) and the power needed by the specific employed controller. Thus, from the elements point of view, the RIS power consumption is given by the summation of the power consumed by each active PIN diode.

III. RIS-ENABLED UAVS

In this section, we provide an overview of the applications of RIS-enabled UAVs. We first discuss the physical limits UAVs that may impact on the network performance. Then we describe two scenarios where RIS-enabled UAVs may provide significant advantages.

A. A Review of the UAV Technology

UAVs are a technology in vogue and are envisioned to be employed for several purposes, such as aerial photography for journalism and movie, express shipping and delivery, and wireless communications. In this paper, we focus on the use of UAVs to create air-ground Line-of-Sight (LoS) links and enhance communication network performance. In this case, a RIS-enabled UAV is goes over a route to serve the network users. The optimization problem of finding the most suitable UAV’s location at any time is solved by a ground controller. The resulting quality of the communication links highly depends on the features of the employed UAV. In fact, according to the physical features of the UAV, the controller

| Operating Frequency [GHz] | Number of Reflecting Elements | RIS Area [m²] | Power Consumption [W] | Ref. |
|--------------------------|--------------------------------|--------------|----------------------|-----|
| 2.4                      | 6 x 8 = 48                     | 0.015        | not available        | [2] |
| 4.25                     | 8 x 32 = 256                   | 0.037        | 1.28                 | [1] |
| 5                        | 8 x 8 = 64                     | 0.004        | not available        | [3] |
| 10.5                     | 100 x 102 = 10200              | 1.02         | 10.56                | [1] |
| 10.5                     | 50 x 34 = 1700                 | 0.17         | 10.56                | [1] |
either creates channels used for a long time period (e.g., when hovering on a certain place), or open up opportunistic windows for one-time transmissions.

In this context, an key performance indicator is the flight time, defined as the maximum time a UAV can spend flying without getting recharged or refueled. This time ranges from tens of minutes to few hours, depending on the model and make and is also influenced by the weight and size of the load. In fact, the payload adds an additional weight to the UAV structure, and the UAV engine has to generate additional thrust to compensate for it. Furthermore, the size, shape, and position of the load influence the UAV flight time. For example, a wide load acts as a sail in the presence of wind, requiring the stability control module of the UAV to spend more energy in compensating for the additional force imposed by the sail: this reduces the flight time.

B. Applications of RIS-enabled UAVs

RIS-enabled UAVs provide a highly configurable solutions for extending the basic two-dimensional network model to the third dimension, fulfilling one of the requisites of future generation networks. The application of this technology spans different domains [4].

Creation of Communication Links. When considering mmWave communications, the presence of a LoS link significantly improves the link performance. On the contrary, blockage may bring to service unavailability due to the high attenuation at mmWave frequencies that strongly limits the propagation by reflection and scattering. When no LoS channel is present, the RIS-enabled UAV may be deployed to create a communication link [5], [6]. In this case, the RIS reflects the incident signal to the desired location, whereas the UAV provides the flexibility needed in a dynamic environment.

Increased Coverage and Capacity. A RIS enabled UAV can be optimally located to assist cell-edge users that may not be directly reachable by the BS [7]. Indeed, the signal transmitted by the BS impinges the RIS elements which, via beamforming, irradiate a signal reaching cell-edge users. Another solution to improve coverage provides the adoption of Intelligent Omni-Surfaces, i.e., particular RISs having antenna elements on both sides of the meta-surface, thus capable of reflecting signals on both sides: when mounted vertically, they enable reflections in two areas of the cell. Irrespective of the employed RIS technology and thanks to the 3D mobility of UAVs, it is possible to extend the cell coverage and to increase the network capacity in a dynamic set-up. In the latter case, RIS-enabled UAV can overcome the limitations imposed by blockages by dynamically adjusting the location of the RIS or by moving it to areas with a high user concentration to help in the resource allocation process.

Wireless Information and Power Transfer The large number of Internet of Things (IoT) devices in future networks is challenging for energy management. Indeed, all these devices are battery-powered and there is a fundamental need for smart solutions to reduce their power consumption or provide external power supplies. To this end, wireless power transfer enables the charging of batteries without wired connections and RIS-assisted UAV may support the charging process. In fact, thanks to the high mobility provided by UAVs and the low-energy demand of RISs it is possible to automate charging and convey power to multiple IoT nodes while at the same time also providing energy to the UAV. During the charging process, it is also possible to encode information in the signal that delivers the power in what is commonly known as wireless information and power transfer. Thus, RIS-enabled UAVs not only dynamically deliver power to IoT nodes, but at the same time collect the information they generate, hence optimizing the network resources.

Enhanced Physical Layer Security (PLS). A RIS-enabled UAV provides a configurable network that can be prevent attacks such as eavesdropping thanks to directional jamming signals. The UAV mobility enables the optimal deployment of the RIS to optimize the secrecy rate. Furthermore, when the attacker can be identified, the UAV can track it to provide continuous secrecy to the communications. Lastly, by using Intelligent Omni-Surfaces it is possible to control the secrecy rate over a pre-defined area. The optimal deployment of RIS-enabled UAVs can also be exploited for physical layer authentication, providing dynamic access to users to the network’s services when needed.

IV. APPLICABILITY OF RIS-ENABLED UAVS

Before deploying RIS-enabled UAVs to serve a communication network, key features such as the path loss of the resulting channel and the maximum flight time needs to be considered. In this section we provide a numerical evaluation of the path loss incurred by the communication channel ground-RIS-ground, considering different carrier frequencies and RIS’s sizes. We provide the results considering the flying policies of different countries, which regulate the UAV flying altitude. Furthermore, we will show how the size impacts the flight time of different UAV models. Lastly, we provide a case study on the effectiveness of RIS-enabled UAVs in supporting security to the network. Here instead we consider the impact of the RIS size on both the security and the flight time of the UAV.

A. Path Loss Modeling

We consider a RIS of negligible thickness on an horizontal plane. Furthermore, we consider transmitter and receiver are in the far field with respect to the RIS.

We compute the path loss according to the model in [8], focusing on the transmission frequency and the area of the RIS. Fig. 1 shows the variation of path loss with respect to the transmission frequency and the number of elements of a RIS. For an UAV’s flying altitude of 50 m. We notice that, irrespectively of the transmission frequency, increasing the number of elements reduces the path loss. On the other hand, for a given number of elements, the path loss increases with the carrier frequency. Therefore, to be able to exploit the advantages brought by mmWave and THz frequencies, RISs shall be equipped with a large number of elements to avoid incurring in a prohibitively high path loss. However we notice that a higher number of elements also means a higher
Fig. 1. Path loss of the user-RIS-BS channel for a UAV height of 50 m.

RIS size and therefore a higher weight to be carried by the UAV. Although usually the size of the elements depends on the carrier frequency, the inverse proportionality between these two measures is not sufficient to cope with the increase in path loss. Therefore, although elements are smaller for higher frequencies, the required number of elements still renders RISs larger at higher frequencies.

B. RIS-Enabled UAV Flight Time

As we previously stated, the UAV flight time depends, among other factors, on the weight of the payload. Furthermore, when considering a RIS-enabled UAV, additional power is required to control the RIS. The additional power is related to both the activation of elements and powering the controller. We here show how this affects the flight time of different UAV models. Fig. 2 shows the flight time vs. the number of RIS elements for UAVs ZEO X4 [9], Noa 6 [10], and IF1200 [11]. Our choice on the UAV models is motivated by the information made available by the producers. We model the flight time and power consumption according to [12]. With the increased number of elements the size of the RIS increases, and consequently its weight. We here consider a carrier frequency of 10 GHz, and an RIS area going from $9 \cdot 10^{-3} \text{ m}^2$ to $9 \cdot 10^{-2} \text{ m}^2$. Due to the additional weight, the flight time decreases when increasing the area of the RIS. The most severe effect is obtained considering the ZEO, where the flight time decreases from 50 min to 35 min. Therefore, although an increased RIS size leads to smaller path loss values, the flight time significantly decreases. This highly impacts scenarios where the UAV needs to deliver a service hovering for a long time, or the UAV needs to fly a long path to reach its destination.

C. Applications to PLS

Due to their high configurability, RISs represent a fruitful technology for PLS. For instance, by suitably placing a RIS, we can improve the communication link to the legitimate receiver and at the same time alternate or null the link to an eavesdropper, assuming to know its channel. In a scenario where multiple users shall be securely served, multiple RISs would be particularly useful, but with high costs. The use of a RIS-enabled UAV reduces the deployment costs and provides a flexible solution, thanks to the UAV freedom of movement. Therefore, although a RIS-enabled UAV may require a higher initial investment, it gives economic benefits in the long term, as it does not require network reconfiguration when moving or deploying new RIS.

A researcher trend investigates the advantages for PLS provided by RIS-enabled UAVs. Authors in [5] considered the uplink of several single-antenna users that communicate with a BS over a no LoS channel: they therefore propose to exploit an RIS-enabled UAV to convey a secret signals to the BS by jointly optimizing the trajectory of the UAV, the phase shifts of the RIS, and the user’s transmit power. Considering a multi-antenna BS communicating to a single-antenna user, the authors in [7] exploit a RIS-enabled UAV for the downlink: by optimizing the phase shifts of the RIS and the beamforming vector of the BS, the system’s total energy efficiency is improved. Authors in [6] consider a non-LoS channel and exploit a RIS-enabled UAV to create a communication link: the UAV, in addition to holding the RIS, plays the role of a relay between the transmitter and the receiver to create a self-interference at the UAV. By optimizing the number of reflecting elements and the altitude of the UAV, good performance in terms of outage probability, ergodic capacity, and energy efficiency are achieved. The authors in [13] considered a downlink communication, where the RIS-enabled UAV reflects the received signals from the BS to other UAVs at lower altitudes, which in turn broadcast the signal to ground users in their assigned area: the performance of the symbol error rate and outage probability of the RIS-assisted UAV-UAV communications is studied.

V. APPLICATIONS PERFORMANCE

In this section, we consider two examples of applications of RIS-enabled UAVs to communication networks. We design a
novel algorithm to optimally control the RIS phase shifts and the UAV location to maximize either the spectral efficiency (first case study) or the average secrecy rate (second case study). In the first application, we use the RISs to improve the coverage, here measured by the total coverage capacity. The second example pertains PLS as we impose confidential transmissions with respect to an eavesdropper in an unknown location.

A. Increased Coverage

We first consider the spectral efficiency obtained for different numbers of RIS elements and UAV flight altitudes. We consider an uplink wireless communication system where the BS is equipped with a Uniform Linear Array (ULA). We consider four single-antenna users, placed at the corners of a square centered at the BS’s location. We assume that no LoS channel is available from the users to the BS, therefore RIS-enabled UAVs convey the signal to the BS. In particular, a single RIS-enabled UAV is available for each user. The BS uses zero forcing beamforming to mitigate the multi-user interference, and we assume perfect channel knowledge for the beamformer design. While the phase shifts are optimized through non-convex optimization algorithm using coordinate descent, we compute the best location of UAVs via a novel particle swarm optimization algorithm. Fig. 3 shows the average total spectral efficiency versus the number of RIS elements. Considering two Signal-to-Noise-Ratio (SNR) values (i.e., 0 and 5 dB) and two UAV flying heights (i.e., 50 and 150 m). We notice that the SNR is the main factor that impacts on the system’s performance. In fact, while increasing the altitude incurs in a small reduction of the spectral efficiency, increasing the SNR significantly improves the spectral efficiency. We also notice that an increasing number of elements provides a higher spectral efficiency. This is due to the decrease in the path loss value, as shown in Fig. 1.

B. Secrecy Application

Due to the absence of complex cryptographic operations, PLS techniques are particularly suitable for time-sensitive applications. Thanks to these techniques, communication links can be safeguarded from attacks such as jamming or eavesdropping. We here show the performance of RIS-enabled UAV in a PLS application. In particular, we assume that an eavesdropper at the BS’s side might be able to capture the uplink signals. To assess the secrecy in the overall area, we consider a grid of eavesdropper’s locations centered at the BS location, and we report the average secrecy rate, i.e., the secrecy rate averaged over all grid’s locations. This measure is more representative than the classical secrecy rate that considers a specific eavesdropper location. In fact, thanks to the average secrecy rate we are able to characterize the security level with respect to an unknown position of the eavesdropper.

Fig. 4 shows the average secrecy rate considering different number of RIS elements, as a function of the two SNR and UAV height values considered for Fig. 3. We see that the average secrecy rate increases with the number of reflecting elements. We further notice that, although the considered flight altitudes are very different, they do not affect the network’s average secrecy rate. This implies that the path loss is not a determinant factor in the achievable average secrecy rate, as both the channel of the legitimate user and the eavesdropper undergo similar propagation environments.

VI. FUTURE RESEARCH DIRECTIONS

We believe that the following represent some of the research directions that need to be addressed.

• Design of Suitable Models to Account Physical Constraints. The shape and size of the RIS imposes some physical constraints to the UAV flying mechanism. Researchers shall consider the sail effect that the RIS may generate in specific meteorological conditions, e.g., high speed wind. These models will be useful for accounting for these effects and compensate them from both a UAV control and a communication channel point of view.
• **Optimization of the Deployment Time of UAVs.** Due to the additional weight imposed by RISs, we showed that the UAV flight time is considerably limited. Therefore, practical network deployments of RIS-enabled UAV shall consider the timing constraints and orchestrate the available UAVs to minimize the time needed to reach a certain destination and the time in which the UAV needs to be deployed.

• **Machine Learning Controllers.** Recent works proposed the use of machine learning to optimally configure the RIS’s phase shifts. However, these machine learning algorithms may impose additional constraints on the UAV’s resources both in terms of memory and power consumption. This will further limit the flight time. Therefore, researchers shall develop low-complexity solutions to guarantee the benefits brought by machine learning algorithms while avoiding the waste of energy resources.

• **On the Flight UAV Charging.** One of the solutions to increase the UAV flight time is given by charging UAVs while they are deployed. Examples of these solutions include wireless power transfer, where a further UAV could be deployed to convey the energy required by the deployed UAV to guarantee the service continuity. Therefore, researchers should develop suitable optimization frameworks accounting for the additional power consumption imposed by the RIS.

• **Design of Suitable Security Measures.** UAVs are vulnerable to multiple types of attacks, both from a network and a physical point of view. Researchers may exploit the advantages brought by RIS-enabled UAVs to enhance the security of the deployed UAVs. However, such countermeasures shall account for the limitations presented in this paper.

**VII. Conclusion**

The use of RISs on UAVs brings several benefits in terms of configurability for a wireless network by increasing the degrees of freedom. However, when considering mounting a RIS on a UAV multiple practical factors need to be taken into account. In this paper, we highlighted the most important factors, namely the additional power consumption and weight while carrying an RIS. We showed how such factors influence the flight time of multiple UAV models. Furthermore, we discussed the quality of the channel from the transmitter to the receiver through the RIS-enabled UAV in terms of path loss, considering the flying altitudes imposed by different countries and showed the path-loss as a function of both carrier frequency and RIS size. Lastly we showed the performance of this framework in a PLS scenario, introducing the concept of average secrecy rate. We showed via numerical evaluation that the achievable average secrecy rate increases with the number of RIS elements. Furthermore, we showed that the flying height and hence the path loss does not heavily influence the achievable average secrecy rate. We conclude that RIS-enabled UAV are a feasible solution to enhance the network security. However, the practical considerations we outlined in this paper need to be considered before the deployment of these solutions.

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