

RIS-aided Multi-hop Backhauling for 5G/6G UAV-assisted Access Points

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Abstract — Drones are considered to be an important part of future 6G telecommunication systems. Thanks to their quick deployment potential, they provide additional connectivity options in the form of a flying hotspot. However, in such use cases, they typically require a wireless backhaul link to facilitate their proper operation, which might be a challenging task in dense urban environments. One of the potential methods that may be relied upon to connect such nodes is the integrated access and backhaul (IAB) approach, where part of the spectrum allocated to users accessing the base station is used for wireless backhauling. Thus, in this work, we consider the problem of establishing a multi-hop wireless backhaul link following the IAB concept, with the aid of drone relay stations (DRSs) and reconfigurable intelligent surfaces (RISs). We formulate the problem of coverage improvement with a fixed number of relays, assuming certain throughput requirements for the backhaul link. The simulations show that the use of RISs offers a coverage improvement in such a scenario or a reduction in the number of nodes involved in ensuring the required backhaul performance.

Keywords — backhaul link, multi-hop, RIS, UAV.

1. Introduction

One of the key use cases considered with 5G and beyond wireless networks is the provisioning of enhanced mobile broadband (eMBB) services through deployment a lot of small base stations (BSs), constituting the so-called ultra-dense network (UDN). One of the challenges when deploying UDNs consists in providing a backhaul connection from the nodes to the network's core [1]. Solutions relying on wired communication may be unavailable, congested or may offer limited capacity only. Thus, fast and economic deployment of backhaul infrastructure ensuring the required capacity is considered a key enabler for UDNs.

Wireless backhaul systems with relay nodes are one of the solutions often considered in 5G networks within the framework of the integrated access and backhaul (IAB) concept. The idea behind IAB is to serve the end users and relay nodes simultaneously, using wireless links with a single macro BS for extending coverage. Two distinct approaches may be adopted in IAB-based systems. In-band backhauling is the first approach in which the same frequency resources are used for user access and backhauling, resulting in potential interference between these links. The other approach is out-of-band backhauling, where separate frequency resources are used

for user access and backhaul provisioning, thus reducing the problem of potential interference [2].

Among the emerging technologies introduced in 5G systems, unmanned aerial vehicles (UAVs) are recognized as an important part of wireless access networks, as they are capable of providing reconfigurable, on-demand access or may serve as relay nodes. The main advantages of such UAV-assisted wireless communications include low deployment costs, ability to deploy them in emergency scenarios or ability to rely on them as temporary network capacity boosters. Furthermore, the wireless link between a flying UAV and a ground located node typically is of the line-of-sight (LoS) variety, meaning that better coverage and higher communication throughput is guaranteed. With the ability to exercise 3D control over the movement of UAVs in the airspace, devices may adaptively change their locations to improve performance of the communication setup. Therefore, one of the key applications of UAVs is to provide wireless backhaul connectivity to small BSs [3]. In a scenario in which multiple UAVs are deployed as quasi-stationary aerial relay nodes, by optimizing their location and routing path, a wireless multi-hop backhaul link can be established between a small BS and a macro BS.

The deployment and control of a UAV-enriched wireless multi-hop network is a challenging task. The weight, mobility, payload, energy consumption of UAVs and the related battery life are the key constraints and cause performance degradation, making it difficult to incorporate a drone as a reliable node for 5G (or later) wireless networks. Additionally, in an urban environment, UAVs may experience blockages of LoS links due to the presence of tall buildings. This means that a big number of such nodes has to be used in order to provide sufficient backhaul capacity.

In order to overcome these problems, advanced transmission techniques making use of reconfigurable intelligent surfaces (RIS) can be considered to improve the capacity or reliability of wireless links in a challenging scenario, where establishing LoS links between UAVs (or UAV and BS) is not possible or requires an increase in the number of drones in operation [4].

RISs, also known as intelligent reflecting surfaces (IRSs) or large intelligent surfaces (LISs), are arrays containing a large number of reflecting elements that can be used to change the amplitude, frequency or phase of the incident signals [5]. RIS are capable of mitigating a wide range of challenges encountered in diverse wireless networks, by proactively modifying the wireless communication environment and, thus, ensuring

an improvement in capacity, reliability, sustainability, coverage, and security of wireless communication. One of the main advantages of RISs is the ease of their deployment. Relying on nearly-passive devices made of electromagnetic material, they can be mounted on different surfaces, including building facades, indoor walls, aerial platforms, roadside billboards, etc. Additionally, they are more energy efficient than conventional relays, as the phase, absorption, reflection, or refraction of the passive reflecting elements of IRSs can control the incident signals without any need of using RF chains. With their ability to reconfigure the wireless propagation environment by compensating for the loss of power over long distances, they can help in creating virtual LoS links between two transmission endpoints if no direct LoS propagation is possible. Finally, RISs are compatible with current radio technologies, supporting full-duplex and full-band transmissions due to the fact that they only reflect EM waves. Thus, their integration with existing wireless systems is possible without significant hardware modifications of the platform.

When it comes to the use of RISs with UAVs, due to their uniform spatial configuration achieved by deploying them at higher elevations, shorter LoS paths could be achieved. Especially in dense urban environments, RISs may be relied upon to overcome the problem of signal outages caused by high-rise buildings when communicating with UAVs operating at low altitude. Furthermore, with RIS mounted on a UAV rather than a fixed wall or a building, improvements in coverage and flexibility of deployment are achieved as well. RIS-assisted UAVs can be used to reduce channel complexity and mitigate interference affecting wireless communications. Unfortunately, the problem of delayed access and extra energy consumed by UAVs needs to be taken into consideration as well [6]. By optimizing the UAV's trajectory and properly allocating resources to account for the presence of RISs, one may achieve a significant reduction in power consumption – one of the crucial factors in the process of designing UAV-assisted wireless networks.

In this work, following the research described in [7], we consider the problem of placing a drone-based relay station (DRS) and selecting a multi-hop transmission path to ensure backhaul connectivity with a given point (a small BS) with the presence of obstacles shown in Fig. 1. Assuming the backhaul link is realized with the help of radio communications and is part of a 5G system, as well as assuming that specific requirements concerning throughput available at the end node are formulated, we extend the work by adding different configurations of RISs deployed on building facades. With the assumption concerning the required throughput borne in mind, we show that with RIS it is possible to increase coverage when a fixed number of UAVs is used or, alternatively, the number of drones required for providing a backhaul link for a given small cell may be reduced.

The remaining part of this paper is structured as follows. Section 2 summarizes selected works on the topic of positioning UAVs to optimize the provision of a wireless backhaul link. Section 3 introduces the model and the parameters of the system under consideration, as well as provides a basic for-

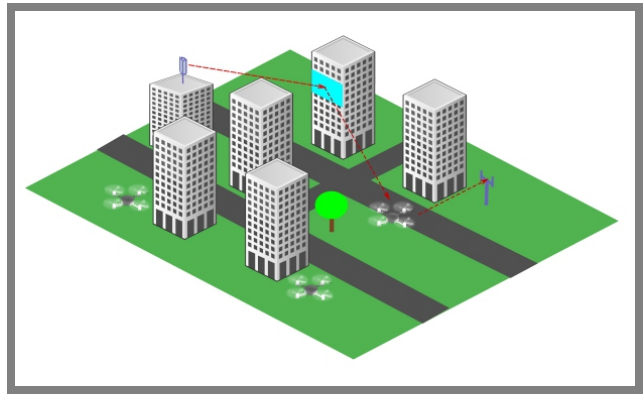


Fig. 1. Application scenario under consideration, with RIS and UAVs used to provide a multi-hop backhaul link between the macro BS and a small BS.

mulation of the optimization-related goal. Section 4 presents the proposed solution and analyzes it based on simulations performed. Section 5 outlines potential further developments concerning the optimization problem, as well as presents other considerations or assumptions related to the investigated scenario. Finally, Section 6 concludes the work.

2. Related Work

The idea of wireless backhauling using UAVs has received a lot of attention within the research community recently, following the introduction of the concept of aerial networks for 6G systems. Although numerous papers focus on the problem of allocating resources for wireless backhauling with the use of drones, only several of them include UAV positioning as one of the optimization parameters.

In [8], the authors present the problem of resource allocation in an in-band IAB scenario, where drones are used as access points providing a wireless backhaul link to the macro BS. Power allocation as well as the locations of UAVs are optimized to maximize network performance in terms of sum rate. However, only single-hop backhauling is considered. Paper [9] considers a similar IAB scenario, however using out-of-band backhauling in the mmWave band and aiming to optimize the drones' locations. A more sophisticated optimization problem is considered in [10], where joint UAV locations, user scheduling and association and spectrum resource allocation are considered for a single-hop UAV-aided wireless backhaul link. A similar optimization problem is also considered in [11], but this case in connection with a cognitive radio network, meaning that inter-system interference is accounted for as well. However, all these research examples fail to consider a multi-hop backhaul configuration. Such a problem is investigated in [12], where maximization of throughput by proper positioning of UAVs, as well as bandwidth and power allocation are considered. Multi-hop networking is also considered in [3], where a game-theory framework is proposed for backhaul optimization.

Introduction of the RIS concept has opened new possibilities for establishing a wireless backhaul link for UAVs. How-

ever, because the idea behind RIS is relatively new, only few recent works consider its application with drone-assisted backhauling. In [13], a high-altitude platform mounted RIS is considered for backhaul provisioning to drone-based BSs, focusing on energy-efficiency. Placement-related and array partitioning strategies for airborne RIS are investigated, as is the optimization of phasing of the array's elements. Similarly, drone-mounted RIS are considered in [14], where a multi-armed bandit problem is formulated for a mmWave backhauling scenario. However, neither of these works consider a hybrid scenario with both RIS and DRS.

3. System Model and Problem Formulation

3.1. System Model

In this work, we consider a UAV-assisted multi-hop backhauling system deployed in an urban environment, where a single macro BS is responsible for providing coverage over the serviced area with the aid of drones. We consider an out-of-band IAB scenario, where a dedicated portion B of the mmWave band is reserved for backhauling purposes. We assume that there are at most N UAVs available that are capable of serving as access points or relay nodes for multi-hop backhaul provisioning. Moreover, we consider an extended Madrid grid [15] scenario, where the macro BS is located in the center of the serviced area, as shown in Fig. 2. Drones operate in a semi-static manner upon being deployed in any of the locations at road intersections (marked with red stars). Furthermore, we consider availability of R RISs mounted on the facades of selected buildings, as these may be used to increase the range of single-hop transmissions.

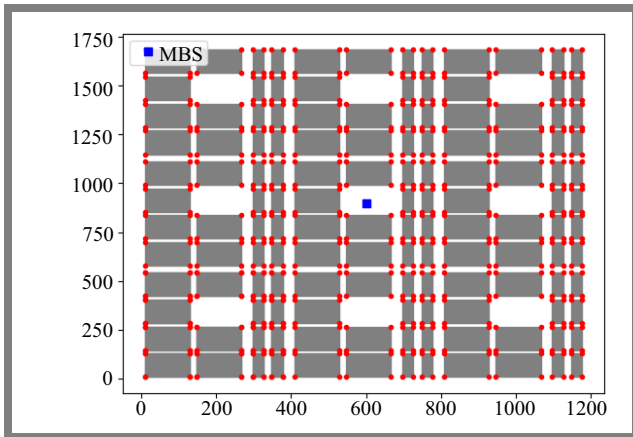


Fig. 2. The layout of buildings, macro BS (MBS, marked with a blue square) and potential locations of relaying UAVs (marked with red circles) for the considered Madrid grid urban environment setup.

Due to capacity-related constraints of the backhaul links, it is assumed that a certain throughput rate needs to be achieved between the macro BS and UAV or between two UAVs in order for a link to be considered available, thus LoS links are considered. We consider that losses caused by reflections from obstacles too high for the considered frequencies to provide

enough capacity for a single hop. However, we account for the possibility of establishing a reflected transmission via RIS, where the received power level depends on the joint attenuation of two paths: transmitter-to-RIS and RIS-to-receiver. The link budget is then calculated based on the path loss estimated with the use of the formulas given below. In the case of a direct mmWave link between two stations (i.e. no RIS involved), the path loss is similar to the free-space path loss, and is given by [16]:

$$PL_{direct}^{dB}(d) = PL(d_0) + 10\alpha \cdot \log(d), \quad (1)$$

where d is the distance, $PL(d_0)$ is the free-space path loss at distance $d_0 = 5$ m, and α is the path loss exponent. In this work, we assume that $PL(d_0) = 39$ dB for a 38 GHz transmission and $\alpha = 2.13$ [9, Tab. 3]. As for the path loss when RIS is involved, we use the same model as in [17]:

$$PL_{RIS}^{dB}(d_{1 \rightarrow R}, d_{R \rightarrow 2}) = PL(d_0) + 10\beta \cdot \log [M^2 (d_{1 \rightarrow R} + d_{R \rightarrow 2})] = g_{bf}, \quad (2)$$

where M is the number of meta-surfaces per RIS, β is the path loss exponent and, finally $d_{1 \rightarrow R}$ and $d_{R \rightarrow 2}$ are the transmitter-RIS and RIS-receiver distances, respectively. Furthermore, we assume that RIS is actively reflecting signals with beamforming capabilities, which is accounted for by adding the gain term of g_{bf} to the formula, which reduces the resulting path loss. We assume that $M = 3$ and $\beta = \alpha = 2.13$.

The average link throughput can be calculated using the modified Shannon formula [18]:

$$C_i = \eta \cdot B^{(eff)} \log_2(1 + SNR_i), \quad (3)$$

where η is the throughput efficiency of the system (fraction of data bits in the total number of bits transmitted), $B^{(eff)}$ is the effective total bandwidth used and SNR_i is the average signal-to-noise ratio of the i -th hop calculated as:

$$SNR_i = \frac{P_i^{(TX)} g_i}{\sigma^2}, \quad (4)$$

with $P_i^{(TX)}$ and g_i being the transmit power (constrained as $P_i^{(TX)} \leq P_{max}$) and the channel gain of the i -th link, respectively, and σ^2 representing the noise component. Channel gain can be calculated accounting for the path-loss and antenna gains of the link as $g_i = G_i^{(Tx)} G_i^{(Rx)} 10 \log PL_i^{dB}$, where $G_i^{(Tx)}$ and $G_i^{(Rx)}$ are the transmit and receive antenna gains, respectively, and PL_i^{dB} is calculated using Eq. (1) or Eq. (2) for the direct or RIS-aided links, respectively. Furthermore, we assume that η and $B^{(eff)}$ can be calculated following the 5G system specification [19].

3.2. Problem Formulation

The aim of this work is to maximize the coverage of the macro BS, providing backhaul capable of achieving minimum throughput C_{min} with the aid of at most N UAVs operating as access points or relay nodes. Each UAV may be position at one of the predefined locations, with the drone's location given by $L_n = (x_n, y_n)$, where (x_n, y_n) are Cartesian coordinates.

Thus, the optimization problem can be formulated as:

$$\max_{\{L_1, L_2, \dots, L_n\}} |A|, \quad n \leq N, \quad (5)$$

where $A = \{L_k, \forall k : Q_k = 1\}$ is the set of all possible locations of a UAV-based access point at which backhaul connectivity to the macro-BS can be provided. Q_k is the connectivity indicator of access point location L_k defined as:

$$Q_k = \prod_{i=1}^n q_i, \quad n \leq N, \quad (6)$$

where q_i denotes the availability of connection via the i -th hop of the backhaul link formulated as:

$$q_i = \begin{cases} 1 & \text{if } C_i \geq C_{min} \\ 0 & \text{otherwise} \end{cases}, \quad (7)$$

Using Eq. (3), the value of C_i is calculated for the i -th link and it can be translated into an SNR requirement of SNR_{min} . When RIS is included in the communication process in one of the hops, this particular link is still considered to be of the single-hop variety, despite RIS supporting the transmission. In such a case, the throughput calculation formula accounts for the joint path-loss of two paths in communication with RIS: $Tx \rightarrow RIS$ and reflected path $RIS \rightarrow Rx$. Thus, Eq. (2) is used for estimating channel gain.

4. Solution and Exemplary Evaluation

4.1. Proposed Solution Including RIS Availability

For a given environment with obstacles (e.g. similar that presented in Fig. 2) and any two points within that area, we can establish if these two points are visible to each other (i.e. have a clear LoS path) using the algorithm described in [7]. In our case, Lee visibility algorithm was applied to graph $G(V, E)$ that contains the set of all building edges, E , and the set of their corner vertices, V , with all of them constituting the set of points for which visibility is calculated. This means that for each point $v_i \in V$ we find a set of points visible from the set of the remaining vertices $\{v_j \in V - v_i\}$. Then, given the resulting visibility graph V_g that contains the edges between the vertices that are visible to each other, we can apply Dijkstra's algorithm to select the shortest path through successive LoS hops.

In this work, we extend the algorithm to account for new possible paths created by an RIS being installed on a building façade. Using Lee's algorithm, we are also able to find all visible points from a given RIS. If two points are visible to RIS, then a link may be established between them with no extra DRS involved. To proceed further, for every installed RIS, we find a set of points that are visible from that particular RIS. Then, we add an edge to the previous visibility graph, for each potential pair.

After having made the points that can communicate through an RIS visible to each other, we still need to apply Dijkstra's algorithm to find a backhaul path to any given point. In order

to find that path, we define different costs for direct edges between two points and for indirect edges that go through RIS, while also taking into consideration the expected rate of any edge, C_{edge} , which is obtained using Eq. (3). These costs are obtained using:

$$D_{edge} = \begin{cases} PL_{direct}^{dB} + P & \text{if direct edge and } C_{edge} > C_{min} \\ PL_{RIS} + P & \text{if RIS edge and } C_{edge} > C_{min} \\ \infty & \text{otherwise} \end{cases}, \quad (8)$$

where P is a fixed penalty per hop to guide the search towards paths with least hops, and ∞ is a sufficiently large number indicating that the edge does not satisfy the rate requirement and, therefore, should be avoided if possible.

4.2. Simulations

Two scenarios are compared in the simulations: the case where there are no RISs, and where two RISs are installed in the middle of the square. These RISs provide virtual LoS paths between any two points that are visible to the RIS within the obstacles, the channel passing through the RIS also includes a beamforming gain of g_{bf} , as mentioned previously. These points belong to the set of feasible DRS locations which is obtained from the buildings' corners. Table 1 lists the simulation parameters assumed.

Tab. 1. Summary of simulation parameters.

Parameter	Value
Transmission power $P^{(Tx)}$	100 mW
RIS beamforming gain g_{bf}	15 dB
Noise power σ^2	-131 dBm
Throughput efficiency η	0.82
Effective bandwidth $B^{(eff)}$	18.72 MHz
Required SNR: SNR_{min} (corresponding to minimum throughput C_{min})	41, 31, 21, 11 dB (200, 150, 100, 55 Mbps)

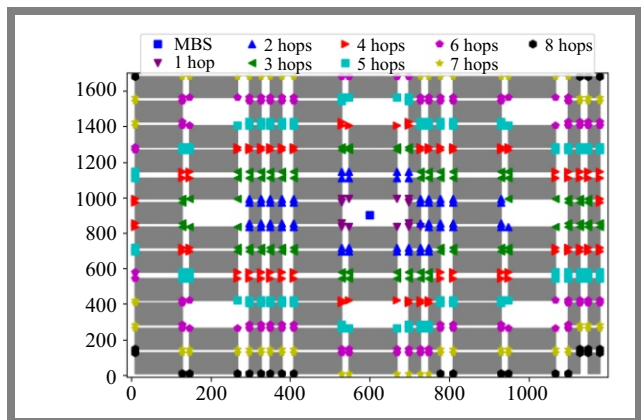


Fig. 3. Required number of DRS hops to reach each point is indicated by the marker color and shape. Notice that not all map is reachable with a maximum of 8 DRS hops.

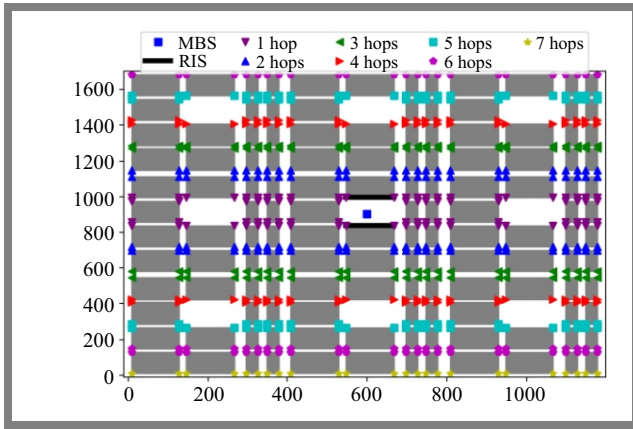


Fig. 4. Number of DRS hops required to reach each point when two RISs are installed at the marked location. Seven DRS are almost sufficient for covering the entire map.

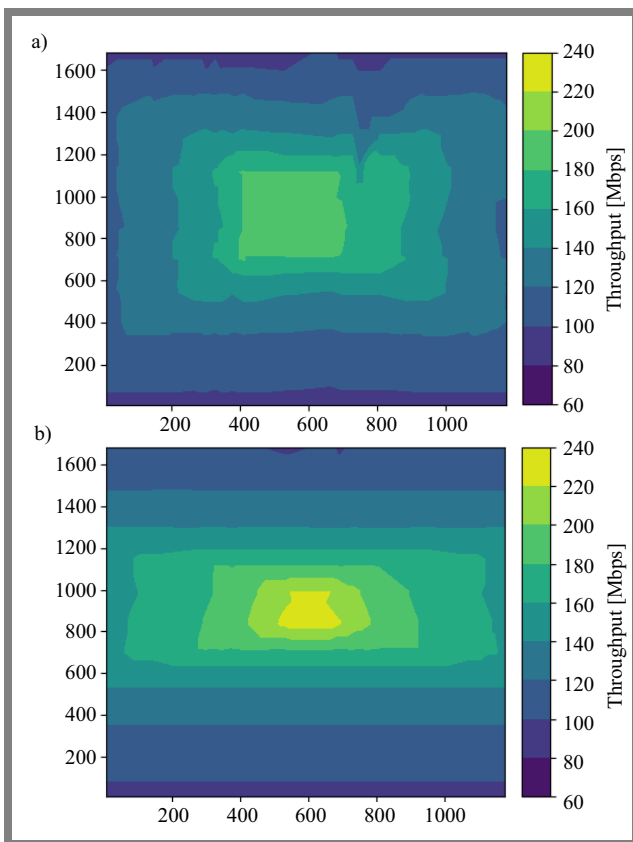


Fig. 5. Heatmap showing the distribution of achievable rates. Part a) shows a scenario with no RISs installed, whereas part b) shows the results obtained with two RISs installed at locations indicated in Fig. 4.

The first results presented in Fig. 3 indicate the number of DRS hops required for establishing connectivity between each point and the considered set of points. In this case, we assume that $SNR_{min} = 31$ dB and no RISs are installed. We compare these results with the scenario in which $R = 2$ RISs are installed (Fig. 4), which clearly shows the MBS may be reached from farther destinations. Furthermore, fewer hops are required for reaching the same destinations as marked in Fig. 3, and the entire whole map may be covered with 7 hops

only, whereas 8 hops were needed for covering almost the entire map without RISs, as shown in Fig. 3.

Next, the achievable rate of each point on the map is obtained and the two scenarios are compared by plotting heatmaps illustrating achievable rate distribution (Fig. 5). Note that to obtain the rate at any point, we need to find the path of selected hops providing connectivity to that particular point and then select the minimum rate between any two hops as the maximum throughput achieved at that point. Figure 5 illustrates the improvement in reachability and throughput that is achieved when only a single location is supplemented with RISs. This improvement arises from both the new virtual LoS paths and the increased signal power resulting from beamforming gain.

Finally, Fig. 6 shows different bar plots for different SNR requirements and illustrates the number of reachable points within the set of all feasible points shown in Fig. 2 (i.e. 600 points). For each SNR requirement, we increase the number of allowed DRS hops N up to 8 maximum. With the SNR requirement of 41 dB, we notice that without the deployment of any RISs, we can only reach a maximum of 3 points, as the distance and, therefore, the path loss between feasible points limit reachability, regardless of the number of DRS hops. Similarly, when deploying RISs, and regardless of N , we can only reach a maximum of 50 points, which is a great improvement in terms of reachability.

For further illustration, we plot this specific scenario in Fig. 7 to better understand the rationale behind this behavior. We can observe that the distance between endpoints of long building edges causes a path loss which prevents the establishment of links satisfying the SNR requirement. In a scenario in which RISs are installed, the beamforming gain allows the establishment of links through the RIS and to the other side of the long buildings. This is a clear limitation of our simplified selection of feasible points (i.e. building corners). To overcome this issue, the middle points of long building edges can be also added to the set of feasible points in order to increase the density of points and, therefore, reduce path loss values when selecting successive hops. Otherwise, more RISs can be deployed at appropriate locations to stretch reachability even further. As for the other figures with higher SNR requirements, we can observe that all points can be reached at a faster rate by increasing N in the case where RISs are installed.

5. Future Outlook

So far, we have investigated only the coverage problem for RIS- and UAV-assisted multi-hop backhauling. The provision of backhaul capacity within a significant area is a crucial task. Other important factors can be also accounted for. Energy efficiency may be considered to reduce the number of DRSs needed to provide the required capacity. Furthermore, reducing transmission latency of the backhaul link, with each additional DRS introducing a processing delay due to the decode-and-forward procedure, is an issue of key significance

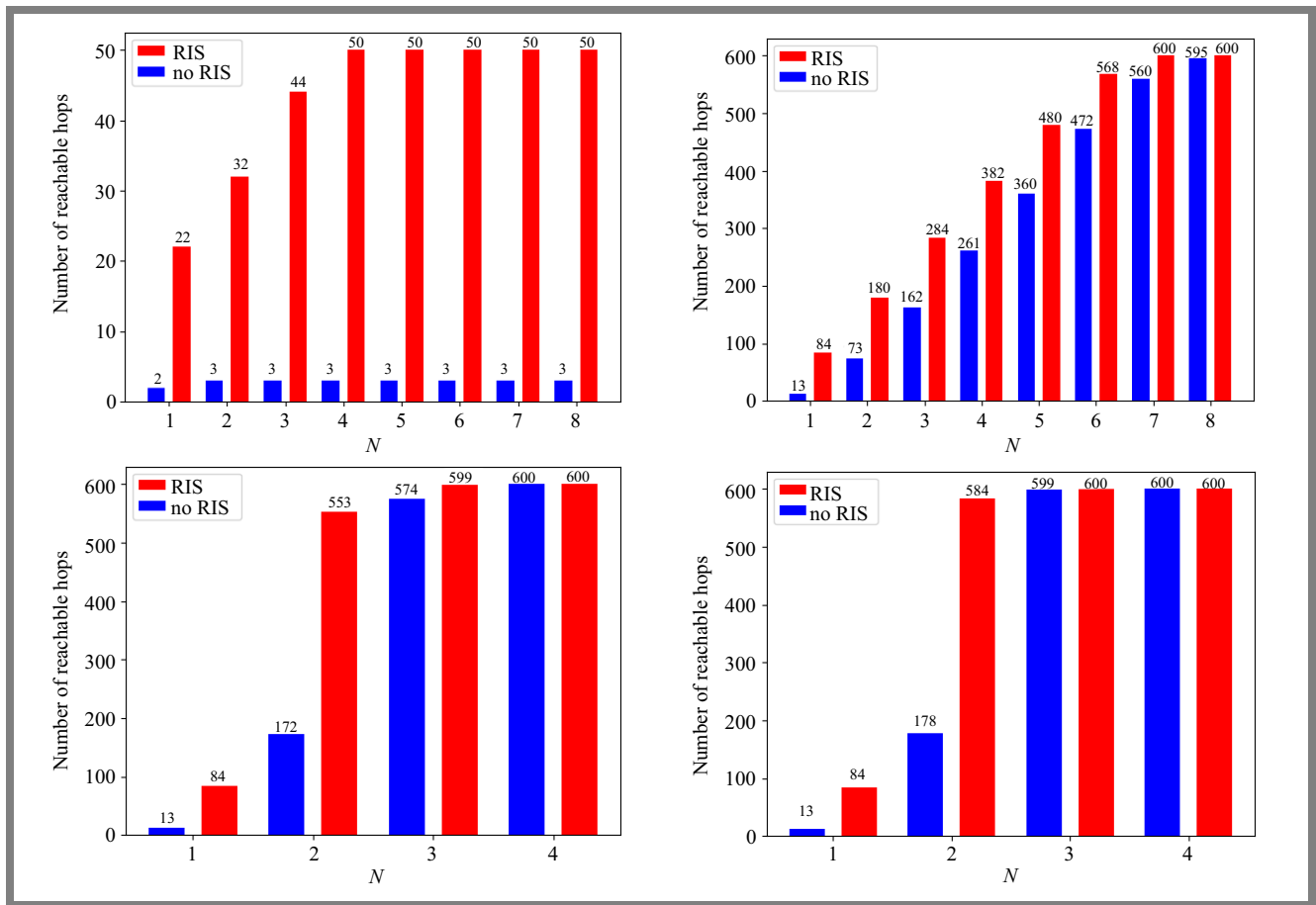


Fig. 6. The bars show the number of reachable points in the map for the SNR requirements of 41 dB (a), 31 dB (b), 21 dB (c), and 11 dB (d). For the stringent requirement of 41 dB, we observe that reachability is limited by the distance between feasible points and, therefore, an increase in the number of DRS hops does not improve reachability.

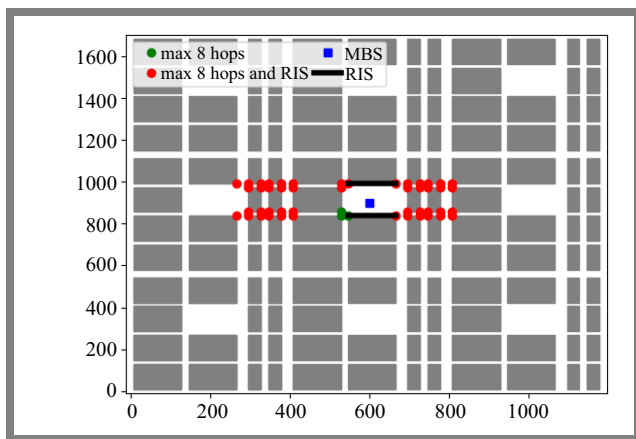


Fig. 7. Reachable points with and without the deployment of RISs for an SNR requirement of 41 dB. Notice that an increase in N does not improve reachability.

as well. In light of the above, the following joint optimization criteria should be considered:

- achieved throughput – the total data rate achieved in a multi-hop link, depending on the propagation conditions of each hop,
- energy consumption – the amount of energy required for deployment and operation of the DRSs involved in the

creation of a multi-hop link, including also the amount of power consumed for transmitting signals (front-end processing),

- introduced latency – the delay in transferring information, taking into account both the propagation delays and the processing delays caused by additional signal processing performed at DRSs (signal decoding and reallocation of resources, if required).

Furthermore, we can also consider different and more complicated RIS availability configurations. So far, we have considered only fixing RIS to building facades. In the next steps, we will investigate the positioning of DRSs based on our knowledge of the availability and configuration of RISs deployed, with potential changes to their locations taken into consideration as well. One can consider the use of mobile RISs that may be mounted e.g. on vehicles or UAVs, thus providing a higher degree of freedom when it comes to their deployment. Such a scenario will require advanced tools for optimizing the path selection process and DRSs placement. Therefore, both conventional optimization-related and machine learning tools will be taken into consideration in future investigation. Additionally, use of additional context information that may be stored in databases, including, for instance, radio environment maps (REMs), will be considered to further improve

performance of the optimization algorithms developed. Finally, when the in-band IAB configuration is investigated, the problem needs to be considered a general resource allocation problem with new, significant types of interference, where the same time-frequency resources are allocated to end users or backhaul links.

6. Conclusion

In this work, we studied the idea of establishing a multi-hop backhaul link between a macro BS and an UAV-mounted hotspot with the use of drone relay stations and reconfigurable intelligent surfaces. With this contribution, we aim to optimize network coverage by maximizing the number of locations at which drone access points may be deployed, observing the minimum throughput constraints applicable to the multi-hop link. We show that with the use of RISs, it is possible to increase the coverage by extending the individual links between the macro BS and UAVs, or between two UAVs. Furthermore, we propose some improvements and topics for further studies focusing on this particular area, which shall be investigated in our future research.

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