Unleashing the Potential of Aerial RISs in Post-Disaster Scenarios

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Abstract

Conventional wireless network infrastructures are known to be susceptible to strong perturbations such as the ones caused by calamities. With this regard, whenever facing an emergency, it is vital to ensure reliable connectivity within the disaster-struck zone. Therefore, in this paper we promote the use of aerial reconfigurable intelligent surfaces (RISs) as a possible solution for supporting any possible damages affecting terrestrial base stations (TBSs). At the same time, we discuss the main differences between the aerial RIS (ARIS) technology and its parent ones, namely the terrestrial RIS (TRIS) and the aerial base station (ABS). To support our vision, we recall hurricane Maria, which affected Puerto Rico in 2017, and propose insightful real-world-inspired simulation results in order to discuss what we believe are the main challenges for a commercial implementation of ARISs in post-disaster scenarios.

Index Terms

Aerial RIS, Post-disaster communications, HAP, Terrestrial RIS, Relay.

I. Introduction

Disasters have always represented and still represent a threat to communities, since they are capable of impairing life, economy, and activities within the suffered region. In fact, the United Nations (UNs) decided to establish *the International Day for Disaster Risk Reduction* (IDDRR), on October 13$^{\text{th}}$, to stimulate all populations and governments in improving their resilience to calamities. This is particularly important nowadays as the number of world's severe earthquakes (of at least magnitude 7.0 in the *modified Mercalli intensity scale*) that happened in 2022 is just twice compared to the first two months of 2023. For example, during the writing phase of this manuscript a tremendous 7.8 magnitude earthquake affected Turkey and Syria, killing over forty thousand people.

One critical phase of the disaster management process regards the development of effective search and rescue (SAR) procedures, which are mostly based on human, canine, or electronic agents. Although humans do not necessarily require to be professionals rescuers, their participation exposes them to huge risks. While the advantages of canine missions are particularly important in case of unconscious trapped victims, even well-trained dogs cannot be supportive when the amount of rubble is excessive. Finally, rescuing the victims by means of electronic equipment leverages acoustic and vibration signals produced by conscious casualties [1].

In any case, the use of wireless communication technologies is indispensable for enhancing the chances of saving lives and minimizing the losses caused by the calamity. Although wireless

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communication systems are often given for granted when it comes to provide daily services, their availability usually becomes insufficient in emergency situations[1]; in fact, the failures of some network infrastructure's parts and the increased service demand could damage, overload, and even isolate them.

The common counteraction in the post-disaster phase is to deploy ad hoc networks; in particular, the ones based on the deployment of unmanned aerial vehicles (UAVs) such as drones or high-altitude platforms (HAPs) are increasingly attracting the attention of academic and industrial communities. This solution can be implemented in various ways, but the most interesting from our perspective are the ones where the UAV carries either a base station (BS) equipment or an RIS [3], which is a programmable surface structure capable of reflecting electromagnetic waves. Fig. 1 provides an illustration of a HAP-mounted RIS for emergency situations.

However, while UAV-mounted BSs are already available in the market (although not yet on a large scale), RISs are still at the prototyping stage [4]; therefore, we would like to emphasize that the discussions about these advanced reflectors (either in their aerial or terrestrial fashions) are based on just a few preliminary experimental results and not on a thorough in-field and commercial experience.

A. Contributions of this Paper

Compared to the existing literature on post-disaster communications, we can summarize the main contributions of this paper by highlighting our proposed:

- Extensive comparisons between the novel ARIS technology and its parents, namely the TRIS and ABS technologies.
- Real-world-inspired case study (based on detailed datasets) demonstrating the potential benefits of deploying an ARIS to support the surviving cell towers.
- Overview of the challenges and open problems regarding the use of ARISs.

B. Outline of this Paper

The remainder of this paper is structured as follows:

- In the next section, we provide context on the existing literature works about ARISs and post-disaster communications (PDCs).
- Then, in Sec. III we discuss the main differences between the ARIS and TRIS paradigms, with a special focus on the deployment aspects.
- Similarly, Sec. IV compares the ARIS technology with the ABS one in terms of hardware, power consumption, susceptibility to disturbances, and delay.
- The fifth and core section of the paper provides insightful simulation results about the potential benefits of the ARIS' deployment in a disaster-prone environment such as the island of Puerto Rico.
  Our simulations leverage stochastic geometry (SG) tools as well as real-world data sets regarding the cell tower's and population density's distributions.
- Sec. VI suggests some future directions of our research and enlists the main challenges regarding the use of ARISs (and especially drones) in post-disaster scenarios.
- Finally, we summarize and conclude this manuscript in Sec. VII.

[1] For a broader perspective on post-disaster communications, we invite the reader to refer to our survey [2].

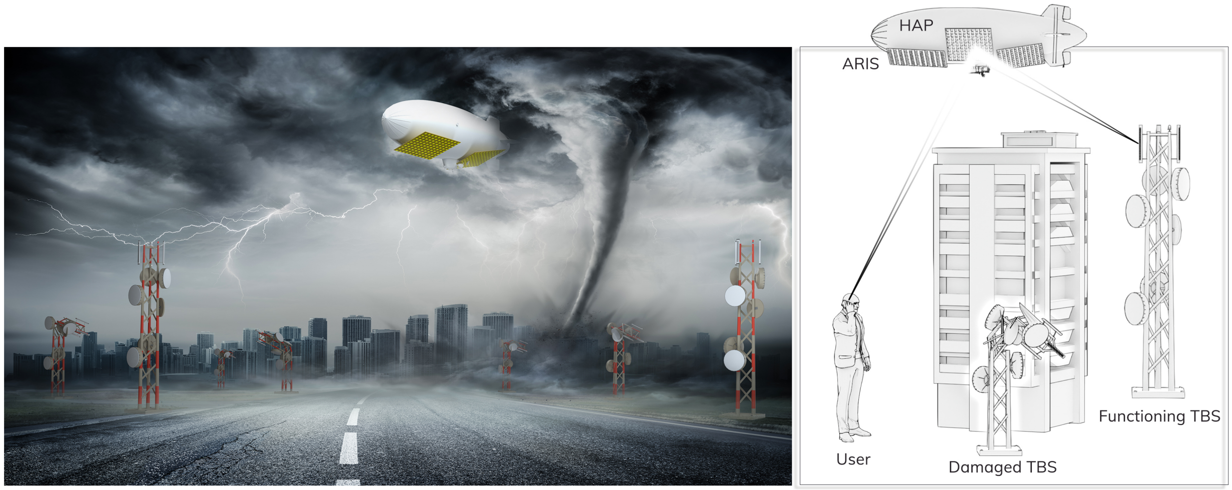

Fig. 1. System figure: ARISs can be deployed in post-disaster scenarios to improve the quality of the communication links between users and surviving TBSs.

II. Existing Works on ARISs for PDCs

Firstly, we should mention [5], where the authors promoted the integration of RISs and UAVs (either as RIS-equipped or RIS-assisted UAVs) to carry on public safety missions; however, the proposed study provided results about the achievable data rate by considering only the serving TBS, without taking into account any possible interferers.

In addition, authors in [1] designed the so-called *pseudo-multilateration*, a novel localization technique which, differently from the classical multilateration one, considers a single moving anchor (for example, a drone) to estimate the distance from a user over time; to this extent, the authors suggested deploying ARISs in order control the channel and find its optimal configuration.

Then, authors in [6] assumed a fixed-wing[2] UAV-mounted RIS to serve trapped UEs under Fisher-Snedecor-F composite fading conditions; the study lead to novel closed-form expressions for the bit error rate (BER), channel statistics, and outage probability.

Finally, our recent work [7] introduced an SG-based mathematical framework to evaluate the network performance in post-disaster scenarios. In particular, we derived the distance distributions, association probabilities, and Laplace transform of the interference in order to compute both the local and the average coverage probabilities in case of a circular disaster-struck area; then, we showed that a reasonably-designed ARIS-aided architecture generally outperforms its ABS-aided and non-aided counterparts.

However, compared to all the aforementioned works, the peculiarity of this paper consists in providing results that are based on data sets extracted from real geographic areas[3].

Moving on, Fig. 2 illustrates a qualitative comparison between the ARIS technology and its parents (TRIS and ABS), while more detailed discussions will be provided in the next two sections.

[2] Despite the limited maneuverability, the authors decided to focus on the fixed-wing design because it is capable of carrying a larger RIS compared to an equivalent rotary-wing design.

[3] Actually, we applied a similar approach in a previous paper about wind-turbine-mounted base stations for rural connectivity [8].

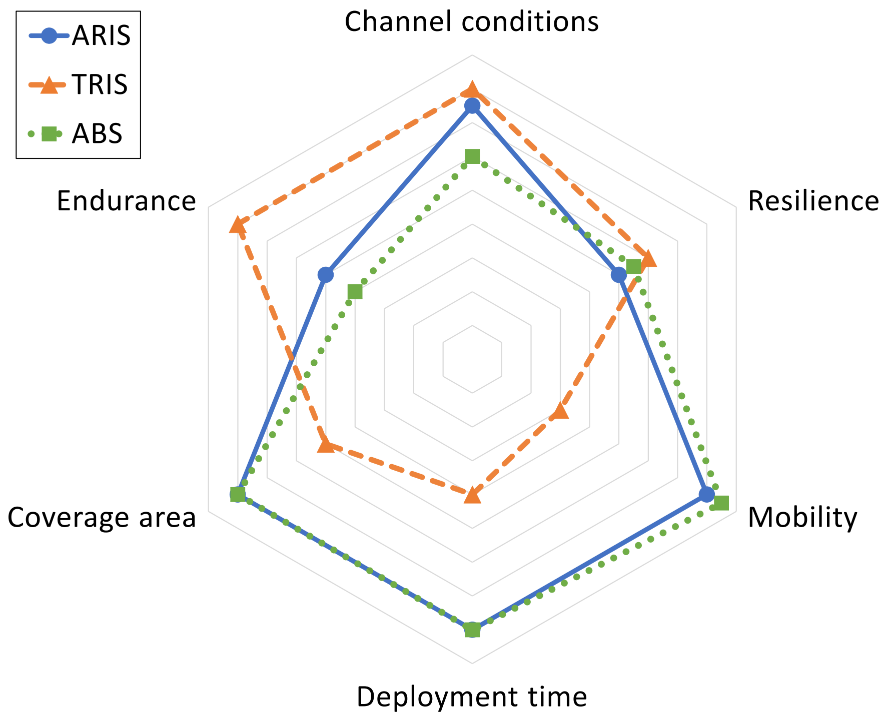

Fig. 2. Radar chart: qualitative comparison between ARIS, TRIS, and ABS technologies.

III. Comparing ARISs and TRISs

This section provides a bird's eye view of the main differences between ARISs and TRISs in terms of channel conditions and deployment.

A. Line-of-Sight (LoS) Communications

In conventional terrestrial networks (with ground users and BSs), the region of influence of a TRIS is more limited than its ARIS counterpart due to substantial differences in terms of surface orientation. Indeed, TRISs are mostly mounted on buildings and therefore they are exposed to just half of the ground plane, hence the coverage region is very limited compared to its ARIS counterpart. However, for similar reasons the presence of multiple non-terrestrial relays (either aerial or space platforms) can strongly promote the TRIS over the ARIS, since the latter are generally facing downwards.

Finally, the high altitude makes the reflected signals less likely to be obstructed by buildings and trees, and therefore one single reflection is usually enough to reach the desired user (often implying negligible signal attenuation). Nonetheless, increasing the altitude also increases the distance to the ground plane, leading to a trade-off between a higher LoS probability and a higher path loss when evaluating the overall channel conditions.

B. Vibrations

Since a TRIS represents a static node, its vibrations are negligible and hence do not lead to considerable channel fluctuations. On the other side, the missions for UAVs, and especially untethered drones, are characterized by persistent vibrations; although using multiple ropes to carry the RIS can help in mitigating the wobbles, these may still be not sufficient for achieving high accuracy in terms of channel estimation and beam steering [9, Sec. II-A].

C. Deployment

Generally speaking, deploying a TRIS is much more time-consuming than deploying an ARIS. Indeed, for the TRIS case, the deployment phase starts from the choice of a suitable site (usually a building facade), and thus it implies complications due to its visual impact and the availability of the building's owner[4] [9, Sec. II-A]. In a post-disaster scenario, however, deploying a TRIS on buildings would not often be feasible due to time constraints as well as the lack of a proper personnel, but deploying it on an ad hoc ground vehicle would still be an option.

Deploying an ARIS (and hence, a UAV) may raise safety issues and privacy concerns (although the latter could be neglected in emergency scenarios). In addition, technological limitations in terms of the UAV's endurance and susceptibility to harsh weather conditions need to be taken into account before starting any mission; such constraints are much more relaxed for the case of a TRIS, since it is supported by a fixed structure. However, some TRIS could have been deployed even before the occurrence of a disaster, hence the fragility of the RIS and the limited resilience of the structure hosting it may represent a critical factor (especially in case of strong earthquakes). Finally, while the TRIS is typically fixed, the ARIS enjoys much higher mobility and relocation flexibility [10].

IV. Comparing ARISs and ABSs

In this section, we overview the main differences between ARISs and ABSs under various important aspects.

A. Hardware

ABSs include several electronic elements (*e.g.*, digital-to-analog and analog-to-digital converters, mixers, and amplifiers for transmission and reception), and the number significantly increases in case of full-duplex (FD) relaying, which evidently leads to relatively high computational costs [9, Sec. II-A]. On the other side, the metallic or dielectric nature of the RISs' patches (properly combined with low-power active components such as switches and varactors) leads to high configurability without any problem related to antenna noise amplification nor self-interference [10]; hence, no complicated electronic circuits and numerous active components are required by ARISs [11], leading also to a smaller probability of failure and hence a higher resilience compared to ABSs. In other words, we can consider the ARIS as a simpler (yet effective) amplify-and-forward (AF) ABS.

Finally, while the BS equipment can be attached to the frame of a drone, if the same vehicle carries an RIS by means of ropes it is more unstable from an aerodynamical point of view, and hence more likely to accidentally collide with other objects; this endows ABSs of a slightly higher resilience and mobility compared to ARISs.

B. Power Consumption

Power consumption is a critical aspect for untethered UAVs, and especially drones. While relays are generally equipped with all the aforementioned active components (which consume a considerable amount of power, apart from the power consumed during radio frequency transmission), the RISs' passive array architecture leads to the same functionalities of large antenna arrays at a fraction of the energy consumption; the only power required by the RIS is to feed its

[4] However, some forms of transparent RIS are currently being developed in order to solve these problems.

control unit [9, Sec. II-A], and hence ARISs are expected to achieve slightly longer endurance compared to equivalent ABSs. However, there is an exception when just a low rate is targeted, and in that case the decode-and-forward (DF) relay would be more energy-efficient [5, Sec. 3.2].

As a reference, the prototype recently introduced in [4] achieved a power consumption as small as $1\,\mathrm{W}$ for a board of 1100 elements clustered in roughly one-fourth of a meter square.

C. Disturbances

ABSs can operate according to various relaying protocols, but one important aspect to take into account is the presence of disturbances such as additive noise and loop-back self-interference. Whenever adopting the AF relaying protocol, the performance of ABSs may be compromised due to additive noise. On the other side, the DF relaying protocol avoids this issue, but requires decoding and re-encoding the signal (which leads to higher computational and energy costs). Furthermore, in case of FD operation mode the effect of residual loop-back self-interference negatively affects the quality of the communication [11].

RISs, instead, are immune from additive noise (but not from phase noises). Finally, when considering a large scale network, it is fair to assume that the RIS will not suffer the interference coming from every TBS, but will be able to detect the signal coming from the desired direction; since a similar assumption cannot be made for the ABS case (unless advanced massive multiple-input multiple-output (MIMO) techniques are implemented at the cost of higher computational powers as well as heavier and bulkier equipment), we conclude by saying that ARISs enjoy better channel conditions than ABSs.

D. Transmission Delay

While FD relaying suffers from high energy and computational costs as well as loop-back self-interference, its advantage is to require only one time slot to transmit a signal. Hence, the transmission delay of an ABS operating in FD mode is comparable to the one of an ARIS; however, a common ABS operates in half-duplex (HD) mode, and suffers from a transmission delay that lasts roughly twice longer [9, Sec. II-A].

V. Real-World Case Study

A. System Setup

For our study we picked Puerto Rico, an island of the Atlantic Ocean suffering frequent exposure to storms and floods. In particular, Puerto Rico has become very famous among the telecom community because of the hurricane Maria and the consequent ad hoc deployment of *Project Loon*'s balloons [12], which was able to support around a hundred thousand users.

In this occasion the existing cell sites' quality of resilience (QoR) was as little as 5%, meaning that only one TBS every twenty survived the calamity. An illustration of this situation is shown by Fig. 3, where 95% of the original TBSs (extracted from the *OpenCellid* data set [13]) have been randomly removed, yet resulting in a considerable overall number.

However, the serving TBS will be selected among a subset of the surviving ones, since we assume that a LoS link (either direct or indirect) is needed by both the user and the ARIS in order to properly detect the signal; therefore, for each possible link we will determine if its ends are in LoS or non-LoS (NLoS) condition by following the stochastic approach presented in [14, Sec. II]. The details about our assumptions on the channel conditions of the ARIS and the ABS are hereby omitted, but can be extracted from our technical paper [7].

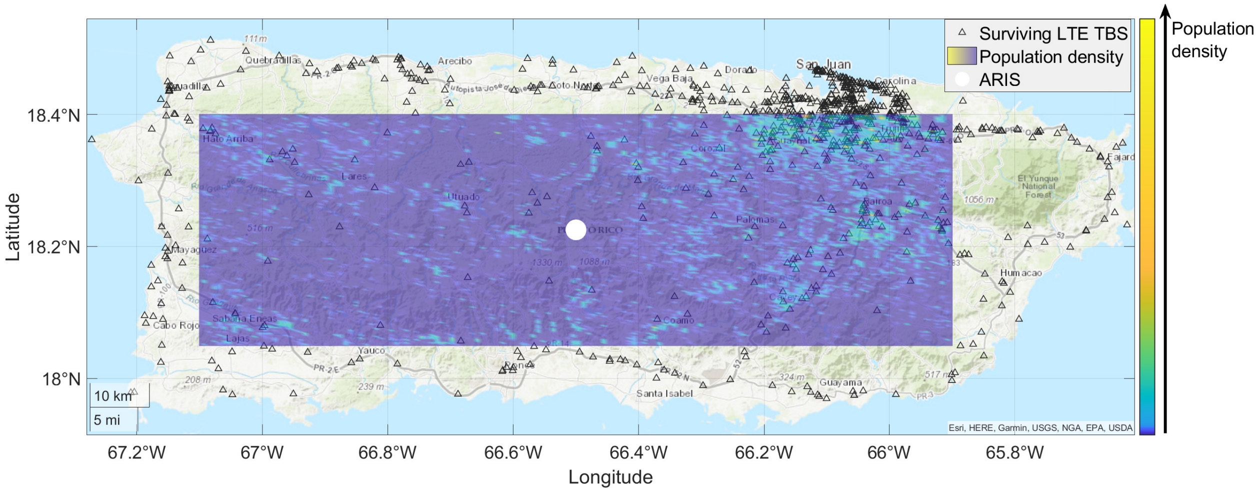

Fig. 3. System setup: the ARIS is deployed at the center of a rectangular area of interest (within which the population density is taken into account) to support the surviving cell towers (the damaged ones are omitted).

TABLE I
MAIN SIMULATION PARAMETERS

Parameter	**Value**
Number of Monte Carlo iterations	$n_i = 10^4$
TBSs' QoR	$\chi = 5\%$
TBSs' altitude	$h_T = 30\,\text{m}$
TBSs' transmit power	$p_T = 20\,\text{W}$
ARIS' altitude	$h_A = 50\,\text{km}$
ARIS' number of elements	$M = 10^6$
Noise power	$N_0 = 10^{-11}\,\text{W}$
SINR threshold	$\tau = 0.3162 = -5\,\text{dB}$
LoS Nakagami-*m* shape parameter	$m_L = 3$
LoS path loss exponent	$\alpha_L = 2.3$
S-curve parameters [14]	$a = 4.88\,;\ b = 0.429$

Finally, for our study we will consider a rectangular area, within which the population density's distribution (as provided by the data set of the *Humanitarian Data Exchange* (HDX) [15]) is taken into account when selecting the typical user. The ARIS is assumed to hover above the center of the area of interest.

B. Results and Discussion

Our goal is to quantify the improvement, in terms of coverage probability, that the deployment of an HAP-mounted RIS can bring in the post-disaster scenarios. To this extent, we partitioned the area of interest in multiple rectangular sub-areas, and computed the coverage probability (averaged over a large number of iterations and weighted on the population density) over each sub-area.

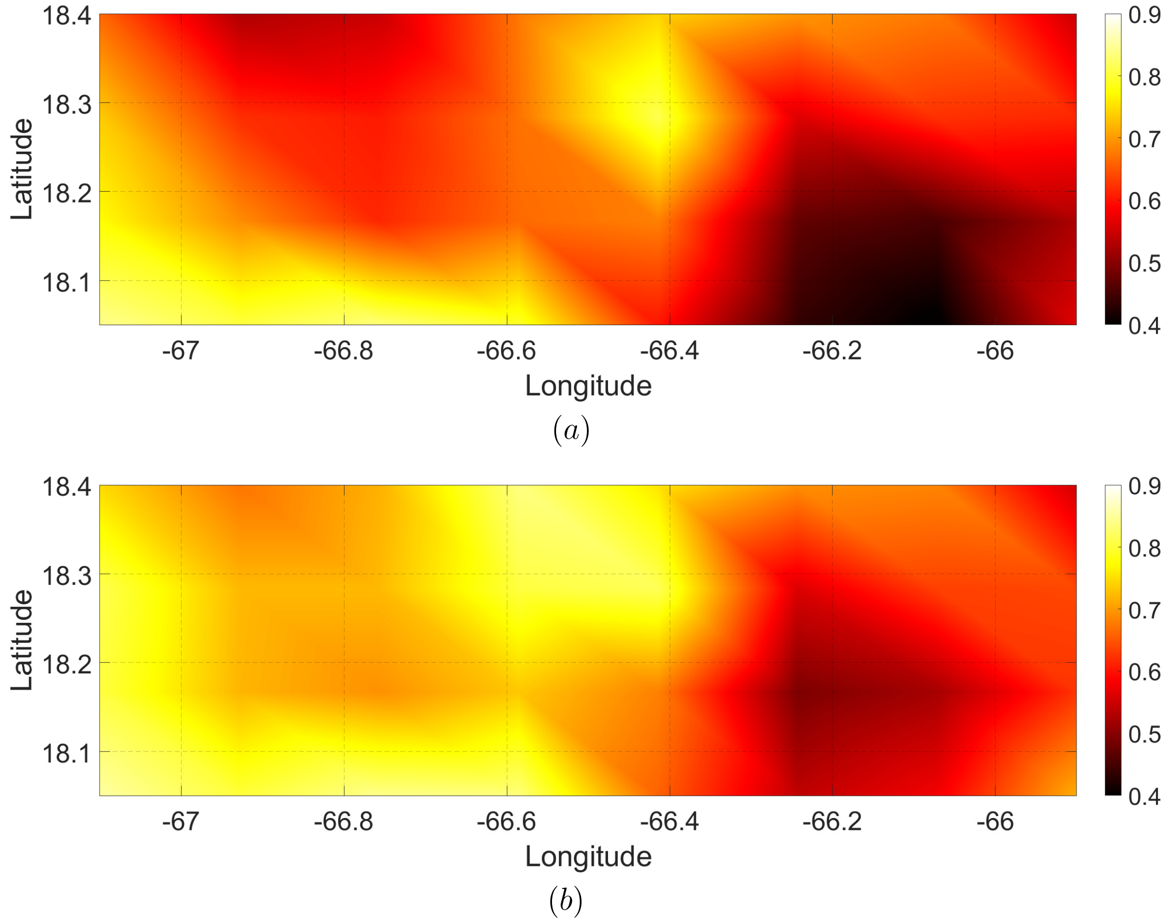

Fig. 4. Coverage probability over the considered area in Puerto Rico when: (a) no ARIS is deployed and (b) a HAP-mounted RIS with one million antenna elements is deployed at an altitude of $50\,\text{km}$ above the center of the same area.

Compared for example with the relay technology, the main advantage of the RIS is that it can be fairly assumed capable of accurately selecting the signals that come from a specific direction and precisely reflecting them along another direction; in other words, the RIS would not cause any interference while the relay would, unless advanced massive MIMO techniques (which are not always compatible with UAVs) are used. Our results have been obtained via Monte Carlo simulations by applying the following procedure:
(i) one user per sub-area is selected based on the population density distribution;
(ii) for each user, the maximum average received power association rule is applied by comparing the power coming from the closest LoS TBS with the power received through the best indirect LoS link;
(iii) the resulting SINR is computed (by taking into account that only direct links provide interference) and compared with the respective threshold;
(iv) the previous points are repeated at each iteration and the coverage probability is computed for each sub-area.
The simulation parameters are listed in Table I. Note that while $M = 10^6$ may seem excessive for an RIS, by scaling the prototype in [4] and considering the weight of each element equal to $10\,\text{g}$ as in [16], this would respectively correspond to an area of almost $250\,\text{m}^2$ and an overall weight of around $10^4\,\text{kg}$, which is compatible with both size and payload capability of a large blimp. Finally, we set an altitude of $50\,\text{km}$ as commonly done in the literature when seeking

wide coverage areas.

Figs. $4(a)$ and $4(b)$ clearly show that properly deploying an ARIS can be vital not only for the users affected by the calamity, but also for the first responders. In particular, we can see massive improvements in the North-West and South-East zones of the area of interest, where the deployment of the ARIS leads to an improvement of around 10-15%; on the other hand, either with or without the ARIS the coverage probability remains fixed at around 60% in the North-East corner, because of the relatively high density of TBSs. In conclusion, by taking the average of the performance over all the sub-areas, the network's coverage jumped from 63.9% to 70.2% when deploying the HAP-mounted RIS (while the average coverage in case of an equivalent ABS deployment would be just 67.4%). Given the extension of the area of interest and the fact that just one RIS was deployed, such a considerable boost was achieved thanks to both the high altitude h_A and the large number of elements M, which allowed the signals coming from the TBSs to respectively take a path with less obstacles and be amplified.

VI. Challenges and Future Directions

A. Challenges

Whenever considering aerial vehicles, both their endurance and resilience to harsh weather represent challenging aspects; in particular, UAVs would strongly suffer in case of prolonged winds and tornadoes, while for example the presence of smoke would affect all wireless communication systems in similar ways.

Moreover, the use of RISs in case of terrorist attacks brings important security concerns due to the fact that they are very sensitive to the directions of the signals (as already mentioned in Sec. IV-C): as an example, any malicious UAV could be placed between the RIS and the serving TBS (or the user) in order to transmit fake information (or eavesdrop the one intended for the user).

Finally, accurate modeling of the channel from/to a drone-mounted RIS is still very complicated due to its continuous wobbling, especially if it operates at high-frequency signals; moreover, given the drone's mobility, channel modeling would become even more challenging if the drone does not inform its serving TBS about its trajectory plan. Therefore, at least for the cases where the reflectors are carried by means of ropes, we believe in the importance of designing aerodynamic and flexible RIS frames to avoid accumulation of rain on the reflector, as well as turbulence and collisions.

B. Future Directions

Following the same direction of this case study, it would be interesting to investigate any possible integration of the ARIS with the closest satellite systems; in particular, by taking into account the expected trajectories of the platforms, the ARIS' location in the tridimensional space (at least for the case UAVs endowed with propellers).

In addition, the system setup may include a swarm of ARISs rather than just a single one, especially in case of relatively-small disaster areas (as we already demonstrated for ABS-aided PDCs [17]). For instance, in some cases deploying multiple drones may be a better solution compared to deploying just one single HAP: indeed, a large fleet would not only lead to a better capillarity of the services (due to both the shorter path losses and higher probabilities of seeing the users), but would also bring the opportunity of easily serving more users at the same time.

VII. Summary and Conclusion

In this paper, we have extensively discussed the deployment of ARISs for PDCs, with a special focus on their differences with ABSs and TRISs; as far as we are concerned, in public safety scenarios the main advantage of aerial nodes lies in their short deployment time, and combining this with a technology that does not provide interference (such the RIS) would make emergency communications much more effective.

In fact, even without considering any dependence on time, our results showed the coverage gain that a HAP-mounted RIS could bring to a Puerto Rican area of several thousands of square kilometers is considerable. However, it is evident that as of today such solution is also subject to several limitations, for instance in terms of controllability in case of strong winds.

Nonetheless, we hope that the huge research interest in this topic will be soon justified by conspicuous governments' investments, considerable technological advancements, and spread of commercial products on a global scale.

Acknowledgements

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