On the Topological Aspects of UAV-Assisted Post-Disaster Wireless Communication Networks

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ABSTRACT

In the context of sixth-generation (6G) networks, emergency management systems based on wireless communications have recently gained increasing interest. Hereby, fundamentals and open problems of post-disaster communications are discussed, especially focusing on their topological aspects. The motivation behind this choice is that whenever a natural or man-made disaster occurs, there is a high chance that the terrestrial communication infrastructure is compromised, and therefore alternative networks need to be deployed efficiently in order to enable the majority of the civilians and first responders to communicate. In this article, we first provide a brief review of existing aerial ad hoc networks for post-disaster communications. Next, we shed light on some new aspects of this problem, which are related to the topology of the network supporting the impacted area. Finally, with the aid of selected simulation results, we show how the cellular infrastructure requirements for a disaster-struck region significantly depend on its location and extension.

INTRODUCTION

A disaster is an event that causes destruction and distress over a large territory. Worldwide, natural as well as man-made disasters are responsible for massive and often unpredictable losses. Especially considering that climate change implies more frequent cataclysms, an efficient network-assisted emergency management system (EMS) is needed in order to predict and identify the incidence of natural calamities, easing response in a timely manner. Note also that when exceeding 72 hours, the chance of survival of trapped victims rapidly decreases, and hence data dissemination and cellular coverage are indispensable in these types of emergency situations.

Therefore, disaster management (i.e., a discipline based on preparation, response, and relief in catastrophic situations) procedures have gained attention in the last decade. All the activities related to disaster management procedures are usually categorized as pre-disaster or post-disaster ones. The former essentially consist of prevention, detection, mitigation, and preparedness phases, and they aim to limit the damage due to a natural adversity by minimizing hazards, for example, by informing people about the incoming danger. On the other hand, post-disaster activities essentially regard damage estimation and repair, recovery, and relocation, and are supposed to last much longer than the former.

The authors provide a brief review of existing aerial ad hoc networks for post-disaster communications. They shed light on some new aspects of this problem, which are related to the topology of the network supporting the impacted area. With the aid of selected simulation results, they show how the cellular infrastructure requirements for a disaster-struck region significantly depend on its location and extension.

Our main objective is to study post-disaster networks assisted by aerial base stations (ABSs), from a novel perspective that focuses on their topological aspects. For example, the authors in [1] surveyed the use of unmanned aerial vehicles (UAVs) in post-disaster scenarios for imagery collection without considering their use as ABSs or the influence of the topology of the affected region. Despite many problems (e.g., trajectory optimization, transceiver design, and intercell/interference coordination) addressed in [2–4], some important aspects such as the extension and location of the disaster area have been omitted.

The main contributions of this article are:
- Disaster assessment is discussed from a novel topological perspective.
- Different fleets of UAVs are quantitatively compared in terms of ergodic capacity enhancement in a wide range of typical disaster scenarios.
- Open problems and conceptual solutions are proposed for intra-region and extra-region emergency communications.

In the rest of this article, we first provide a brief survey on existing solutions for post-disaster aerial communications. Next, we focus on the topology of typical post-disaster communication networks. In particular, we build realistic simulation setups to obtain various insightful results. Before drawing our conclusions, we also discuss open problems that should be carefully addressed in the future to optimize the performance of post-disaster communication networks.

BRIEF SURVEY ON AERIAL BACKUP NETWORKS

Whenever a natural or man-made disaster occurs, the main (terrestrial) communication infrastructure is usually overloaded and subject to partial or total failure. Therefore, it is vital to arrange a reliable backup network in order to ensure sufficient coverage.

We are moving toward a data-centric (rather than voice-centric) world; hence, there is strong interest in designing cellular-based communications for public safety. In fact, some land mobile radio systems take advantage of the latest generations of mobile communications to furnish an adequate emergency broadband service [5].

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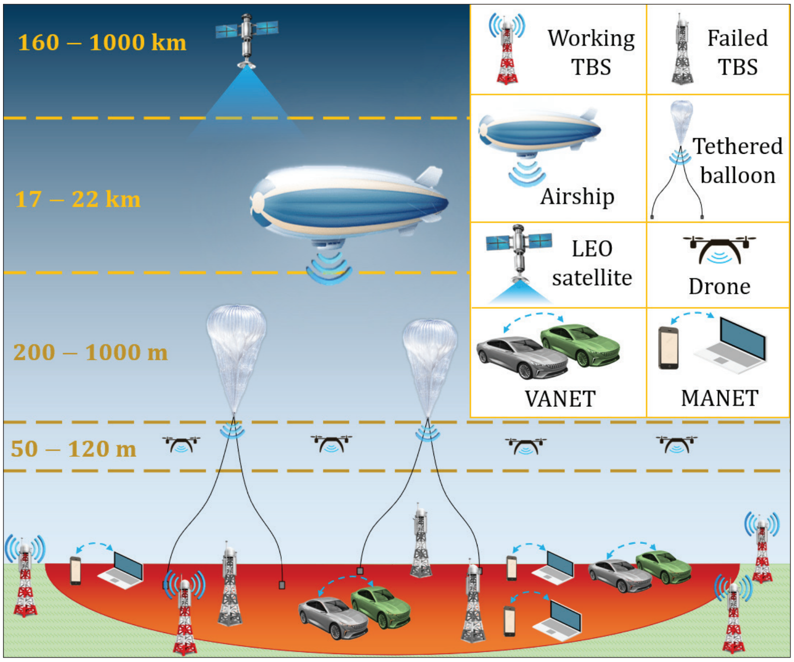

FIGURE 1. Integrated communication systems including non-aerial typical ad hoc paradigms such as LEO satellites, vehicular ad hoc networks, and mobile ad hoc networks. The red area represents the disaster-struck zone.

However, the costliness of terrestrial base stations (TBSs) still represents an important limitation; therefore, research work has been mainly directed toward studying various alternative networks that might also reduce the overall cost of cellular coverage (some of them are illustrated in Fig. 1).

Capable of facilitating fundamental requirements such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), unmanned aerial vehicles (UAVs)[1] can also serve other emergency services [2, 6]. However, this technology has not been fully standardized yet and will probably become mature with the advent of 6G [7]. Indeed, the lack of ubiquitous low-Earth orbit (LEO) satellite constellations or uptilted TBS antennas for providing aerial backhaul, as well as insufficient data rates for ensuring safe coordination of large fleets, are technical limitations that still need to be overcome while reducing the costs of deployment.

The main paradigms of UAV networks are discussed in this section. Manned vehicles such as helicopters and airplanes have also been considered for emergency communications as well, but are now less favorable due to the requirement for a pilot and the concurrent improvements of other unmanned technologies.

LOW-ALTITUDE NETWORKS

Low-altitude platforms (LAPs) typically operate in the troposphere layer; hence, their altitude does not exceed 10 km. These platforms, however, are not suitable for catastrophes caused by storms or hurricanes because strong wind and rain reduce the payload capacity and the reliability of communications, respectively. This subsection introduces the main types of LAPs.

Drones: Despite drawbacks such as limited achievable payload and flight time, as well as high risk of collisions, drones actually represent the most promising technology for emergency communications, due to their advantages in terms of low cost and high mobility, and the fact that they do not require any pilot, to name a few.

Specific designs for drone stations intended to operate in emergency scenarios have been proposed in [4, 8]. The authors of [9] suggested a cooperative fleet of drones made of a grid of ABSs supported by a tethered drone for backhaul and two powering drones for extending their flight time. As remarked in [8], image processing and information exchange (e.g., position, flight trajectory, speed) between UAVs are needed to avoid collisions, especially when maneuverability is limited. This mostly happens in the case of harsh meteorological conditions, for which safe UAV landing procedures are needed.

Tethered Drones: When tethering a drone, higher autonomy and signal strength are achieved at the price of limiting its mobility and relocation flexibility. The optical fiber connection integrated in the tether ensures a better backhaul link, and the power supply enhances the flight time from roughly one hour to even more than a month. Note also that having limited mobility might be an advantage in harsh meteorologic conditions, since the risk of collision is drastically reduced [10].

Low-Altitude Balloons: Interesting research has been carried out to support the integration of light-fidelity (LiFi) systems on low-altitude balloons [11] to conduct search and rescue (SAR) operations, showing that LiFi-equipped balloons can represent a cheap and more versatile alternative to radio frequency (RF) systems (more versatile because LiFi technologies can also work in floods or in the presence of combustible gas leakages). Moreover, this solution may also provide sufficient illumination for rescue teams and victims.

Tethered Balloons: There are several reasons to equip balloons with a tethered link, such as better balloon controllability, more stable power supply, and more reliable data link through the tether. Tethered balloons can be rapidly deployed at considerable altitudes (up to 1 km) above sea level, thus ensuring a considerable coverage area. The effectiveness of such ABSs for disaster mitigation and response was proven in [12].

HIGH-ALTITUDE NETWORKS

High altitude platforms (HAPs), also referred to as high altitude airships, stratospheric platforms, and atmospheric satellites, present various advantages such as wide coverage areas (i.e., tens of square kilometers), favorable channel characteristics, and ease of deployment. Usually, HAPs are deployed at altitudes of 17–22 km. At these altitudes, the energy required for levitating is strongly reduced because of the low turbulence and wind currents. In addition, due to better exposure to the Sun, solar panels and batteries can extend their flight times up to several months.

Compared to satellites, HAPs have the advantages of lower latency, persistence (i.e., the ability to hover over the same area for a long period of time), better image resolution (since they are closer to the ground), and the ability to go back to their base for maintenance or payload reconfiguration [13]. Finally, HAPs are generally faster to deploy than either TBSs or satellites since they just require a few hours to start operating. The most relevant types of HAPs are balloons, airships, and gliders.

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[1] Although the terms drone and UAV are used interchangeably in several works, the latter should actually refer to any flying vehicle with no pilot, including gliders, balloons, and airships.

Balloons: In contrast to tethered balloons, conventional ones usually work as HAPs, since the absence of cables allows them to freely reach higher altitudes (approximately 20 km). Because of this, their coverage radius can exceed 70 km.

Implementing this technology is still very expensive; indeed, Project Loon from Alphabet (i.e., Google's parent company), which aimed to develop a network of high altitude super-pressured solar balloons to furnish Internet access in remote areas, was shut down in early 2021.

Airships: Interesting projects have been initialized to develop airships that address all the requirements for emergency scenarios. One of the most promising innovations, Skyship, has been proposed by the Korean telecommunication company KT Corp. The project aims to realize an innovative platform for safety management. The platform carries a set of drones and car robots equipped with cameras, which are released from the platform to closely investigate the affected area and to establish video calls between civilians and first responders. Skyship would also be connected by means of 5G or LTE technologies to a station on the ground for command, control, and communication.

Gliders: Without using fuel or helium, gliders need batteries and a vast surface of PV modules in order to stay aloft for a long time. Consequently, their design becomes extremely complex compared to other HAPs, since their wide fixed wings will be exposed to intense mechanical stress at very low temperatures. Finally, the use of fixed wings limits the persistence of the aircraft, although it allows reaching the disaster area more rapidly. Despite all the aforementioned challenges, the idea of using a glider-mounted base station (BS) was realized by NASA's Pathfinder-Plus in 2002, and companies such as Airbus, UAVOS, and Softbank's HAPSMobile are now improving their respective gliders (Zephyr, HAPS, and Sunglider) in order to commercialize them soon.

TOPOLOGICAL ASPECTS FOR DISASTER ASSESSMENT

Whenever a disaster strikes, the very first counteraction required is definitely to estimate the damage caused. Keeping in mind the brief overview provided earlier, here we introduce the main topological aspects to consider for choosing the best type of aerial platforms for post-disaster scenarios. Note that UAVs can also play a crucial role by means of the remote sensing instrumentation with which they can be equipped. Indeed, camera-equipped UAVs can determine many features of the disaster area (e.g., hazard maps, dense surface models, detailed building renderings, comprehensive elevation models). Most recent technologies also enable automated map creation in order to rapidly assess the damages inside the affected region [1]. The communication techniques for disaster assessment, however, are out of the scope of this article.

EXTENSION OF THE DISASTER AREA

Estimating the size of the disaster area is vital to succeed in emergency missions. Note that the most diffused technologies for cellular communications are susceptible to disasters, since their infrastructure can take months to recover after a serious failure.

As stated earlier, there are various types of aerial platforms to deploy in disaster-struck regions in order to enhance cellular coverage, each with its own advantages and disadvantages. The knowledge of the extension of the affected region is vital to determine which type of aerial platform best suits the affected area. In addition, the size of this area determines whether an action needs to be taken or, instead, the surrounding cellular infrastructure can provide sufficient coverage.

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GEOGRAPHICAL LOCATION

In order to plan the correct aid for searching and rescuing all the victims trapped inside the disaster region, detailed information about the geographical location of the site is also needed. For instance, a confined disaster area located in the periphery of a small town could still count on the surrounding ground BSs, whereas if a tragedy happens in an isolated village, it would definitely be preferable to send a fleet of drones to support it. Furthermore, when streets and roads are blocked by debris or even destroyed, ABSs are preferred to traditional ground response systems because they can speed up the process of identification of victims, avoiding limited communication services relying on high-latency and low-bandwidth satellite communications.

LOAD DISTRIBUTION

The spatial distribution of the users in the affected region highly affects the type of backup wireless infrastructure that should be deployed after a disaster. For instance, if the users are sufficiently clustered around gathering points, deploying one single aerial platform at a relatively high altitude above each cluster might conveniently imply having negligible interference. If users are very sparsely distributed, instead, the best option might be to deploy a large number of drones in order to locally assist both SAR operations and cellular service enhancement.

NETWORK RESILIENCE AND STATE OF THE INFRASTRUCTURE

The level of resilience of a network can be expressed by the quality of resilience (QoR) metric, a factor between 0 and 1 that directly quantifies the ability of the network to react in failure instances without being perceived by users [14]. Evidently, the state of the existing infrastructure must be known prior to sending ABSs to support the users. For example, some TBSs inside the disaster-struck zone could still work despite the failure of other ones; hence, the locations and conditions of the BSs in the suffered region should be taken into consideration when selecting the type, number, and placement of the backup network nodes. This concept was highlighted in [3], where the framework of UAV-assisted emergency networks in disaster situations depends on the state of the infrastructure. If there are still some active TBSs, ABSs may cooperate with them in order to serve the terrestrial users.

NETWORK PERFORMANCES IN POST-DISASTER SCENARIOS

This section aims to introduce the topological aspects defined earlier in a realistic model simulating a disaster-struck terrestrial network assisted by specific fleets of ABSs.

If the users are sufficiently clustered around gathering points, deploying one single aerial platform at relatively high altitude above each cluster might conveniently imply having negligible interference. If users are very sparse, instead, the best option might be to deploy a large number of drones in order to locally assist both SAR operations and cellular service enhancement.

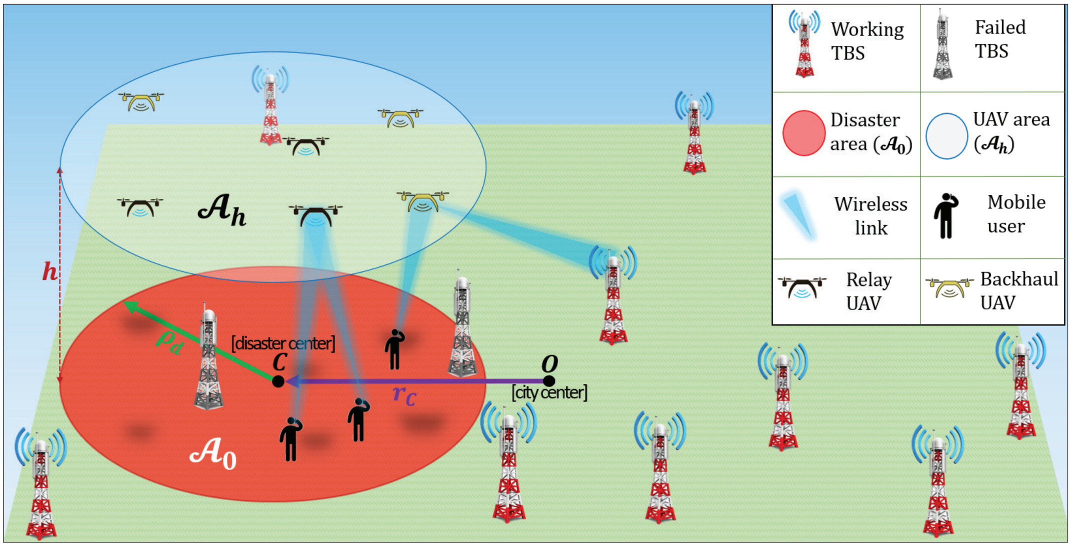

FIGURE 2. Proposed system setup. The TBSs inside the suffered region (assumed circular with radius ρ_d) fail, and thus a fleet of UAVs is deployed above the same region either to provide cellular coverage or for assessment.

SYSTEM SETUP

We model the locations of the nodes as point processes (PPs), which is a common assumption in the literature [2, 15]. In relation to an earlier section, we assume the worst case: a network with null QoR. To compensate for the complete breakdown of the TBSs within the disaster area, which is represented in Fig. 2 by a circle $\mathcal{A}_0$ with radius ρ_d and centered at distance r_c from the town center, a fleet of n_A identical ABSs is deployed uniformly at a fixed altitude h above the disaster area (i.e., scenario 1 in [3]). Each UAV is either in line-of-sight (LoS) or non-line-of-sight (NLoS) condition with respect to the user, independent from the other UAVs.

All the transmitted signals are assumed to experience a standard power-law path loss propagation model with exponent α depending on the type of transmitter, namely TBS, LoS UAV, or NLoS UAV. The serving BS provides the maximum average received power, whereas all other BSs are assumed to interfere.

SIMULATION RESULTS

Assuming a dense urban environment, two sets of simulations are proposed:

- The first one assumes homogeneous Poisson PP (HPPP)-distributed TBSs, and hence, the location of the disaster is irrelevant,
- The second one considers inhomogeneous Poisson PP (IPPP)-distributed TBSs whose density decreases when moving away from the town center; thus, the distance of the disaster from the origin (i.e., the town center) is relevant.

We evaluate the ergodic capacity, R, that can be achieved by means of various fleets of drones, tethered balloons, or HAPs for various values of n_A (which are chosen based on the fact that each type of ABS has its own coverage radius, depending on both altitude and transmit power). The ergodic capacity is the average Shannon capacity given that the signal-to-interference-plus-noise ratio (SINR) exceeds a certain threshold τ. Averaging over 10^5 iterations of the PPs, R is evaluated at 50 points as a function of ρ_d for the HPPP setup and of r_c for the IPPP one. Indeed, the main scope of these setups is to investigate the influences of the extension and the location of the disaster area, respectively, introduced earlier.

Our main question is the following: What is the best fleet of aerial platforms (among drones, tethered balloons, and HAPs) given ρ_d and r_c? In what follows, we show that the answer is not trivial due to the inherent trade-off that exists between providing higher signal quality for ground users and causing higher interference for mobile users served by other BSs.

For the proposed simulations, the bandwidth, SINR threshold, and noise power spectral density are set equal to 100 MHz, –5 dB, and 10^{-12} W/Hz, respectively. Furthermore, for TBSs, drones, tethered balloons, and HAPs, the transmit power p_t is equal to 10, 1.585, 10, and 20 [W], while the altitude h is set to 0, 0.1, 0.5, and 17 [km], respectively. Finally, the exponent α and the Nakagami-m shape parameter m equal 2 for LoS ABSs and equal 3 and 1, respectively, otherwise. The mean additional losses ε are set to 0.005 for NLoS ABSs and 0.692 otherwise.

HPPP-Distributed TBSs: In the first set of simulations, the locations of the TBSs are modeled as a HPPP of density 10 BSs/km^{-2}. The results are illustrated in Fig. 3 when drones, tethered balloons, or HAPs are uniformly distributed over $\mathcal{A}_h$. For the three cases, the black curves are equivalent because they refer to the same system with no UAVs. On the other hand, different nonzero values of n_A have been chosen for each type of vehicle, since they have completely different coverage areas.

Various insights can be drawn from Fig. 3:

- When ρ_d exceeds a few hundred meters, the terrestrial infrastructure becomes insufficient, since R monotonically decreases due to the increasing path loss.
- In general, the optimal n_A decreases as h and p_t increase.
- When deploying LAPs, from Figs. 3a and 3b we can observe that at low values of ρ_d, deploying just a few ABSs is most favorable. This is mainly because more numerous fleets generate a stronger interference. However,

as ρ_d increases, many more ABSs (especially if drones are being deployed) are needed to cover $\mathcal{A}_0$.

- Compared to LAPs, HAPs have a peculiar behavior that can be justified by considering that their h is of a higher order of magnitude than that of LAPs, whereas all the p_ts are relatively comparable.

For values of ρ_d up to 1 km, deploying any HAPs is discouraged, as shown in Fig. 3c. Indeed, in this scenario the user has almost no chance of benefiting from HAPs (despite the latters' p_t being twice their TBSs' counterpart) because there is an excessive difference in terms of their respective minimum distances from the user, namely 17 km for HAPs as opposed to ρ_d for TBSs. This makes HAPs essentially operate as interferers, thus worsening the performance of the network.

On the other hand, when ρ_d exceeds a couple of kilometers, the user is much less influenced by the surrounding TBSs and can now take advantage of the support offered by the available HAP(s).

IPPP-Distributed TBSs: The locations of the TBSs have been generated according to a bidimensional Gaussian distribution with variance 10 km^2 centered around the town center, such that the average number of TBSs within a distance of 100 km from the town center is 1254. Assuming ρ_d equal to 500 m, Fig. 4 describes R as function of r_c when deploying n_A drone BSs. The following insights can be extracted:

- By looking at the behavior of R, we note that the steepest increase always occurs when r_c is approximately three times the standard deviation of the TBSs' distribution. At this value of r_c, indeed, the terrestrial interference becomes weak, as also evident from the case with no ABSs (black curve).
- As expected, deploying a larger number of drones reduces the dependence on r_c, since it reduces the association probability with TBSs as well as the influence of the terrestrial component on the aggregate interference.
- The optimal n_A never reaches 15 and actually tends to decrease to 1 when the disaster is moved far away from the town center. Indeed, deploying even a single drone is usually preferable when the TBSs are sparse, because it keeps the serving distance short while bringing the aerial interference to zero.

In conclusion, it is convenient to deploy a single drone when the affected region is located very far from the town center and is confined within approximately 1 km^2. However, the only solution for much vaster failures would be to increase n_A (as already noted in Fig. 3) independent from r_c, since a very large homogeneous area surrounds the typical user.

INTRA-REGION AND EXTRA-REGION COMMUNICATIONS

An interesting open problem consists in providing a system architecture that enhances the quality of communication:

- Among users inside the affected region
- With the outer world through the cellular infrastructure

These two targets may require different technologies and devices. For example, it is easy to imagine firefighters communicating by portable two-way radio devices (i.e. walkie-talkies operating on public safety bands) when operating inside a burning building, but a longer-range technol-

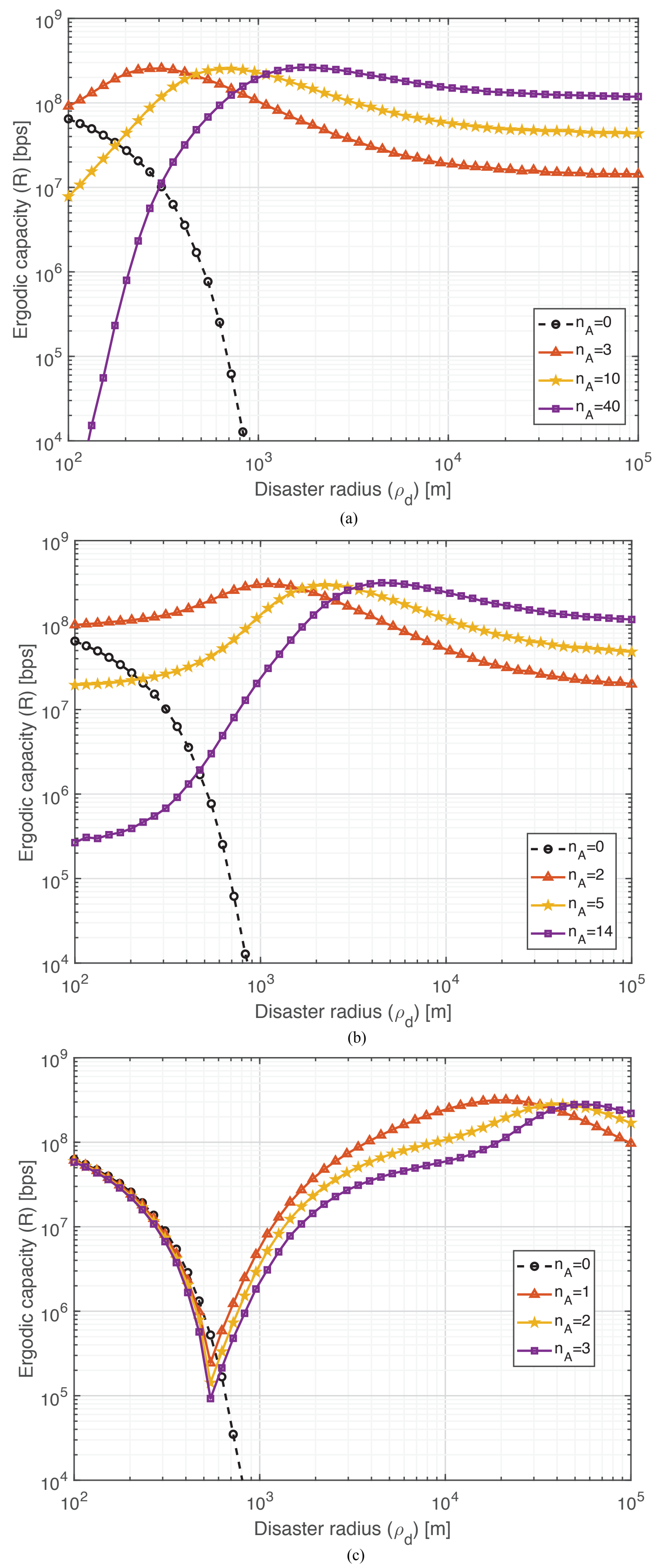

FIGURE 3. Ergodic capacity as function of the disaster radius in case of HPPP-distributed TBSs assisted by: a) drones; b) tethered balloons; and c) HAPs.

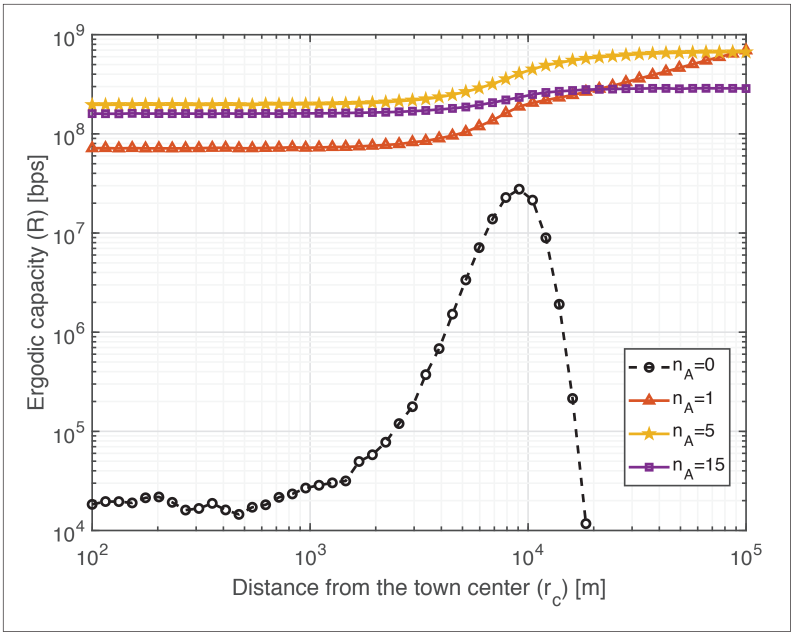

FIGURE 4. Ergodic capacity as a function of the distance between the disaster and the town center when TBSs are IPPP-distributed and ρ_d = 500 m.

ogy such as cellular would be indispensable for extra-region communications.

According to Fig. 2, UAVs can be used as intra-region communication relays for assessment to allow users to share safe routes, shelter locations, and maps, or can be used to establish a backhaul link to provide cellular coverage and connect the users inside the disaster zone to the outer network. In the latter case, ABSs' locations depend on the availability of backhaul links, and hence need to be optimized for maximizing network performance.

Intuitively, backhaul ABSs should be placed in the periphery of the disaster in order to be as close as possible to the surrounding TBSs, but nonetheless further studies are needed to prove this and to investigate the influence of the load distribution and the other topological aspects introduced earlier. Another option could be to make the ABSs fly at different altitudes: the ones needed for backhaul could fly at lower altitudes, compatibly with the LoS conditions, in order to reduce the distance to the closest TBS.

CHALLENGES, CONCLUSIONS, AND FUTURE WORKS

Since no static telecommunication infrastructure can be considered reliable when exposed to harsh calamities, implementing ad hoc aerial networks in a timely manner is an important target for future 6G networks. In fact, some crucial technical challenges still need to be solved: for example, tethered LAPs and HAPs have limited mobility and often require excessive time for deployment. On the other hand, untethered LAPs are limited by short flight times and struggle to find reliable backhaul links. Finally, managing large numbers of aerial vehicles while avoiding obstacles and optimizing their trajectory is a complex task that still requires further research.

In this work, we have discussed the main topological aspects of disaster assessment and network architectures in order to evaluate the ergodic capacity and determine the best aerial fleets to deploy in typical emergency situations. In the future, more complex setups where the UAVs' locations and cardinality are optimized depending on the topology of the network should be considered. Finally, we have shown that a similar approach can be useful for intra- and extra-region communications management, which also deserve further studies.

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