Abstract—The number of disasters has increased over the past decade where these calamities significantly affect the functionality of communication networks. In the context of 6G, airborne and spaceborne networks offer hope in disaster recovery to serve the underserved and to be resilient in calamities. Therefore, this paper surveys the state-of-the-art literature on post-disaster wireless communication networks and provides insights for the future establishment of such networks. In particular, we first give an overview of the works investigating the general procedures and strategies for counteracting any large-scale disasters. Then, we present the possible technological solutions for post-disaster communications, such as the recovery of the terrestrial infrastructure, installing aerial networks, and using spaceborne networks. Afterward, we shed light on the technological aspects of post-disaster networks, primarily the physical and networking issues. We present the literature on channel modeling, coverage and capacity, radio resource management, localization, and energy efficiency in the physical layer and discuss the integrated space-air-ground architectures, routing, delay-tolerant/software-defined networks, and edge computing in the networking layer. This paper also presents interesting simulation results which can provide practical guidelines about the deployment of ad hoc network architectures in emergency scenarios. Finally, we present several promising research directions, namely backhauling, placement optimization of aerial base stations, and the mobility-related aspects that come into play when deploying aerial networks, such as planning their trajectories and the consequent handovers.

Index Terms—Post-disaster communications, airborne networks, spaceborne networks, 6G, backhauling, optimization.

I. INTRODUCTION

While the story of wireless communications tells us the astonishing growth of the achievable data rates over various mobile generations, the increasing research and business interests on the idea of ubiquitous connectivity are much younger. Therefore, wireless communication experts expect that the sixth generation (6G) technology will be the first to pay attention to unconnected and under-connected environments such as low-income, remote, or disaster-struck regions. In this context, many specialized researchers and entrepreneurs are trying to design and implement alternative network architectures and strategies specifically meant to enhance the performances of the current wireless communication systems, since they are particularly susceptible to calamities (see Fig. 1).

In 2021, almost one hundred million people have suffered from natural hazards. Therefore, several organizations and companies have provided them with tangible support in such circumstances. For instance, Alphabet’s Project Loon, in collaboration with AT&T and T-Mobile, provided connectivity to more than a hundred thousand Puerto Ricans after Hurricane Maria destroyed the local network infrastructure. Although the balloons deployed by Alphabet enabled just essential connectivity services, it was an impressive achievement to successfully control their flight from Nevada by using machine learning algorithms [2]. Furthermore, right after the earthquake in Haiti on August 14, 2021, International Telecommunication Union (ITU) and the Emergency Telecommunications Cluster (ETC) collaborated in filling the consequent connectivity gaps experienced by the suffered region. In particular, they assessed the status of the telecom services via a mapping platform called Disaster Connectivity Map (DCM). Satellite phones and Broadband Global Area Network (BGAN) terminals were provided by ITU to Haiti [3]. Finally, it is worth mentioning Elon Musk’s recent efforts in providing a reliable backup Starlink satellite network to both the Kingdom of Tonga [4] and Ukraine [5], which experienced Internet disruptions due to a tsunami and a conflict with Russia, respectively.

Spatial networks (SNs) including non-terrestrial nodes such as aerial base stations (ABSs) and/or satellites can strongly contribute to providing sufficient coverage and capacity at relatively low costs and short deployment times. In SNs, the ABSs and satellites operate at very different altitudes; therefore, designing the physical and networking layer is quite challenging. For instance, different channel models need to be investigated for characterizing the air-to-ground (A2G), air-to-air, space-to-air, and space-to-ground (S2G) communication. Moreover, energy-related considerations for HAPs and satellites should be considered since they are mostly solar-powered. Following similar considerations, both power plants and transmission lines are usually susceptible to large scale disasters. Ref. [6] developed and tested a prototype for an autonomous anti-disaster solar-powered BS connected to the core network via satellite links.

Other interesting projects on developing post-disaster communication networks are project Lantern [7], Baculus [8], and portable cell initiative [9]. Project Lantern is a platform based on the long range (LoRa) protocol and aims to support disaster recovery efforts. It includes a hardware that is able
to autonomously provide wireless fidelity (WiFi), app-based services (essentially meant to help finding supplies), and share useful data to all users through the cloud. Also, machine learning (ML) is used to make a chatbot assist emergency responders (ERs) by sharing important information. On the other hand, Baculus creates a WiFi mesh network, where the users are equipped with a so-called divining rod (i.e., an antenna that guides them towards the closest WiFi access point). The divining rods are continuously updated via satellites about the configuration of the mesh network, in order to help more users to connect. Alternatively, the portable cell initiative project builds portable and temporary systems acting as cell towers, to be deployed in any unconnected environment. In particular, the so-called micro-cells come in a plug-and-play fashion and are characterized by a high level of resilience. They can interconnect with each other in order to create a mesh network which relies on satellite backhaul in order to provide 2G connectivity, even without new SIM cards.

In post-disaster scenarios, connectivity represents a challenging issue and therefore it has gained importance in research over the last few years. One main reason for this is the difficulty faced when assessing the damages since a relatively long time is needed to identify the exact zones that lost connectivity after the calamity. Moreover, the disaster victims can be trapped in the rubble, making it hard for emergency responders to locate and rescue them. Several paradigms can be considered for re-establishing the connectivity in post-disaster scenarios. Let us take wildfire detection as example: apart from conventional solutions such as satellite imaging and remote camera-based sensing which are slow and relatively unreliable, the Internet of things (IoT) can be combined with unmanned aerial vehicles (UAVs) [10] or even being used in an infrastructure-less manner. Indeed, IoT-enabled devices can communicate to each other and essentially create a wireless sensor network (WSN) for informing the users about any significant perturbations on their surrounding environment. To this extent, LoRa technology is often used in order to transfer data for long distances with low power consumption, at the price of a quite limited capacity. Moreover, novel drone-assisted mesh network architectures, such as the so-called UbiQNet [11], are capable of combining image processing and deep learning for finding the neighbouring first responder nodes.

Some other interesting paradigms that have been explored in the literature in order to achieve a networking layer are delay-tolerant networks (DTNs) and software-defined networks (SDNs). The former rely on the Store and Forwarding routing mechanism for making up to the absence of a direct path between source and destination [12]. Software defined networks instead are meant to decouple forwarding devices’ data plane from control plane, in order to ease both the management and the control of the network [13]. These two paradigms can be conveniently combined in emergency scenarios.

As connectivity is at the heart of humanitarian response in disaster situations, this paper aims to solicit the up-to-date literature on the key aspects of wireless post-disaster communications (PDCs), including both terrestrial and non-terrestrial technologies, as well as the consequent issues involving the physical and the networking layers. Furthermore, the proposed work offers relevant simulation results, which can be used by network operators and institutions affected by a calamity, in order to estimate the network’s performance depending on the considered setup circumstances (e.g., the type and number of available nodes as well as the size of the disaster area).

A. Related Surveys

In order to properly describe the significance of information and communication (ICT) technologies in disaster scenarios,
many survey papers have been recently published. For example, authors in [14] reviewed different artificial intelligence (AI) applications for analyzing and processing big data from social media platforms in emergency scenarios. Similarly, [15] reviewed social-aware data dissemination approaches and their difference from traditional data dissemination in disaster situations. In addition, the latest advances regarding the Fog-Assisted Disaster Evacuation Service (FADE) architecture can be found in Ref. [16].

The work presented in [17] is an overview of non-image-based techniques for accurately counting people in both indoor and outdoor environments in disaster scenarios. The authors of Ref. [18] presented another exciting survey on the role of large-scale 3D networks such as hybrid satellite-aerial-terrestrial networks in emergency scenarios, their architectures, trends, and challenges. A more specific review on UAVs’ path planning in smart cities affected by disasters has been recently proposed in [19], where network security aspects are also considered.

A comprehensive review on regulatory and standardization aspects of public safety networks (PSNs) can be found in [20]. Furthermore, Ref. [21] reviewed emerging paradigms for PSNs, primarily focusing on how to converge land mobile radio (LMR) and long term evolution (LTE) technologies. Authors in [22] also compared LMR and LTE in PSNs, with a special focus on the software environment needed for evaluating the key performance indicators (KPIs). In a recent survey [23], the authors discussed future designs for PSNs to manage emergency settings, since in the context of 5G and beyond networks it is required to exploit more advanced technologies such as autonomous decision-making systems and to combine advanced technologies, such as network functions virtualization (NFV) and software-defined networking.

Alternatively, [24] surveyed different multihop ad-hoc network paradigms, including mobile ad hoc networks (MANETs), vehicular ad hoc networks (VANETs), and DTNs, and discussed their importance in the context of disaster response. A review on rescue entities’ mobility models for MANETs in disaster-struck areas can be found in [25]. Authors in [26] studied disaster recovery solutions from the perspective of users and network solutions such as device-to-device (D2D) and dynamic wireless networks (DWNs), respectively. Similarly, [27] presented an overview of the current state of the art of communication systems for mitigating natural disasters, focusing on methods for achieving resilient routing, vulnerability assessment, and reinforcement of existing networks. For non-resilient infrastructures, Ref. [28] presented the network-in-a-box concept, which consists in fitting all the required software and hardware modules in portable devices, resulting in a dynamic and versatile architecture. Authors in [29] covered the resilience issue as well, showcasing various solutions, including D2D, UAVs, and IoT. The latter technology is extensively discussed in [30], where IoT-enabled flood search and rescue (SAR) systems are critically surveyed and a novel IoT-aided integrated flood management framework based on water-ground-air networks is proposed.

Authors in [31] presented a tutorial-like overview of packet-switched networks by focusing on their fast data-plane recovery mechanisms, from traditional layer-2 (i.e., data link layer) network technologies to programmable network paradigms and protocols. Also, [32] presented a state-of-the-art review that categorizes routing protocols for UAV-assisted VANETs based on design and functionality. Finally, in [33], wireless technologies for disaster recovery and healthcare applications were reviewed and compared based on bandwidth, range, and throughput.

A summary of the above surveys and reviews is presented in Table I.

TABLE I RELEVANT SURVEYS AND REVIEWS

| Year | Main focus | Ref. |
|------|------------|------|
| 2013 | Regulations and standards | [20] |
| 2016 | Resilience, ad-hoc networks’ deployment, routing | [27] |
| 2017 | Hybrid satellite-aerial-terrestrial networks | [18] |
| 2018 | MANETs, VANETs, DTN | [24] |
| 2019 | Indoor and outdoor non-image-based people counting technologies | [17] |
| 2020 | Autonomous decision-making systems, NFV, SDNs | [23] |
| 2021 | Wireless technologies for resilient networks | [29] |
| 2022 | Paradigms, physical and networking layers, challenges | This paper |

B. Contributions

Based on the relevant surveys discussed above, and to the best of the authors’ knowledge, there is no single survey that distinctly reviews the updated communication technologies and issues in post-disaster situations. Since communication is a prominent part of establishing post-disaster networks, it is pertinent to analyze the connection between disaster situations and communication technologies from various aspects, including technical issues, applications, and challenges. Therefore, this paper offers an overview of the main features of PDCs, with particular attention to ad-hoc aerial networks. We can thus summarize our contributions as follows:

1) We provide an up-to-date survey of PDCs to project the reader in the perspective of the 5G and beyond generation of wireless communications. In particular, we extensively discuss the most relevant research efforts done over the last decade to design powerful wireless technologies for PDCs and try to solve recurrent physical and networking layer problems;
2) We also present stochastic-geometry-based simulation results for two realistic post-disaster network setups, and consequently discuss how to achieve efficient network planning in such scenarios;

3) Given the numerous aspects deserving further researchers’ attention, we discuss inherent challenges and present what we believe are the most exciting directions for future works in the area of post-disaster wireless communications. We specifically discuss relevant topics such as modulation and coding, backhauling, placement, trajectory and scheduling of movable nodes, handover management, and content caching.

C. Organization

The rest of the paper is organized as follows. Sec. II discusses the most relevant wireless technologies for disaster management and recovery. In Sec. III, we review the main physical layer issues, with a particular focus on the most common channel models as well as the techniques for improving energy efficiency in emergency scenarios. Nonetheless, other literature works referring to inherent aspects such as coverage, capacity, radio resource management, and localization are extensively discussed. In addition, the same section offers two realistic use cases about wireless coverage in disaster environments and exploit a stochastic geometry approach for our numerical simulations. On the other hand, Sec. IV provides an overview of some recent works on the networking layer aspects of integrated space-air-ground architectures, routing, delay-tolerant networking, and software-defined networking. Finally, Sec. V shows the main future research challenges, followed by our conclusions in Sec. VI. The organization of this paper is schematically displayed in Fig. 2.

II. WIRELESS TECHNOLOGIES

In post-disaster situations, a timely counteraction is generally required. Therefore, many wireless technologies have been specifically designed or even re-adapted for serving victims and first responders. In this section, we discuss literature works that recently proposed solutions for improving PDCs by categorizing them use cases about wireless architecture, namely terrestrial, aerial, or space enabled networks. A schematic view of a comprehensive network architecture for PDCs is illustrated in Fig. 3.

A. Recovery of Terrestrial Networks

The most recent occurrences of calamities have often demonstrated that wireless networks are very susceptible. Whenever the terrestrial infrastructure gets damaged, it is preferable to consider repairing it before resorting to other ad-hoc solutions. In this context, the authors in [34] have analyzed the recovery phase of a communication network, evaluating the advantages of D2D and cellular communication systems operating in underlay mode. Furthermore, Ref. [35] has investigated the three possible disaster network scenarios, namely congested, partly functional, or fully isolated, including important considerations on spectrum allocation. Contextually, the authors in [36] have promoted RAPID TIMEER, a system for recording and reporting (via texts, images, and voice) that works independently from both power and telecommunication infrastructures.

The authors in [37] propose the use of cyber-physical systems, especially in public buses and drones, to develop a mobile edge infrastructure, where the buses host as BSs, computation units, and power resources, and thus capable of supporting drones for covering hard-to-reach areas.

Finally, Ref. [38] suggested deploying the so-called movable and deployable resource units (MDRUs)\(^1\), which essentially are vehicle-mounted base stations, as a comprehensive solution for satisfying the needs of users in disaster recovery situations. Some of the main advantages of this solution are indeed represented by its agility, prompt installation, and carrier-free usability.

B. Installation of Aerial Networks

Since the recovery of terrestrial networks in disaster-affected regions is usually a long process, many of the existing works focus on quicker solutions, such as using aerial networks, where airborne platforms (drones, balloons, gliders, airships, etc.) working as flying BSs. Depending on the height and resources of the BSs, we can broadly categorize them into low-altitude platforms (LAPs) and high-altitude platforms (HAPs).

1) LAPs-based Solution: A large number of works discussed LAPs usage in PDCs. For example, Ref. [39] reviewed disaster management applications and challenges using UAV networks, especially when combined with WSNs and cellular networks. Similarly, authors in [40] extensively discussed UAV-aided disaster-resilient networks from a 5G perspective, including fruitful considerations on the simultaneous occurrence of UAV and D2D communications and the power control strategies. Furthermore, [41] recently presented the main logical elements to take into account when deploying ABSs, where various types of UAVs are compared for typical post-disaster network setups. Authors in [42], instead, introduced a distributed and scalable message-based system relying on electric vehicles (EVs) and UAVs that allows to connect shelters by properly partitioning the suffered region (assuming it is considerably large). Finally, the main targets of UAV-aided networks, namely ubiquitous coverage, relaying, and information dissemination, were extensively discussed in [43] together with some design considerations and performance-enhancing techniques.

A recent trend shows a considerable interest in using optimization tools for aerial networks-assisted post-disaster communications. For example, the authors in [44] used particle swarm optimization (PSO) to adjust UAVs’ antenna altitude and beam angle for post-disaster networks. The developed framework allows to effectively optimize coverage under the transmit power constraint. Similarly, the authors in [45] proposed another optimization-based work for UAV-aided disaster

\(^1\) Although these units are typically terrestrial base stations, in our paper the acronym ‘TBS’ exclusively refers to any node of the fixed terrestrial infrastructure, such as a cell tower.
communications (i.e., a macro BS supported by UAVs serving hard-to-reach clusters of users) and validated their framework for ensuring high energy efficiency by jointly optimizing UAVs’ deployment and resource allocation. Then, works such as [46] proposed a unified framework that considers UAVs’ trajectory, scheduling, transceiver design optimization in case of emergency. Similarly, the authors in [47] used a genetic algorithm (GA) for evaluating improvements in terms of throughput when the flying BSs are optimally placed; in particular, the study showed that the performance of the network can generally be improved by increasing the number of ABSs and decreasing their altitude. Also, Ref. [48] recently presented a novel approach to rapidly detect users’ clusters variations in a post-disaster situation, where data ferry UAVs’ path planning is contextually optimized to connect the highest number of nodes in a reasonable amount of time. Furthermore, authors in [49] proposed an integrated aerial-ground network for swift communication recovery to maximize the time-weighted coverage (i.e., the integration over time of the coverage area weighted by a time-dependent function) for a given deployment strategy.

The use of ABSs and D2D technology can extend the coverage for PDCs. For instance, the authors in [50] proposed a linear programming algorithm for obtaining a suboptimal solution for the problem of maximum rate and coverage of UAV-enabled networks with underlying D2D communications. However, the latter work neglects effects of both small-scale fading and non-line-of-sight (NLoS) transmission. Within the same context, [51] introduced two optimal transceiver designs schemes and a shortest-path-routing algorithm to construct efficient multihop D2D links in a post-disaster situation.

Besides the aforementioned physical layer issues, various works tackled the network layer problems for PDCs. For example, [52] discussed the layout of the aerial emergency ad-hoc network (EANET) for both ad-hoc on demand distance vector (AODV) and zone routing protocol (ZRP), eventually promoting the latter since it generally leads to a higher packet delivery fraction (i.e., the ratio between the number of packets generated at the source and the number of packets received at the destination). Furthermore, the study in [53] suggested a UAV-DTN based on a decentralized near-cloud infrastructure with LoRa technology to provide low-power transmission for long distances. The authors investigated the performances of the network (i.e., long-range detection/messaging and detec-
tion under rubble) in both inside and outside environments, in order to comprehensively test the proposed technology. Another work [54] recently introduced a UAV-assisted DTN that takes into account the importance of UAVs’ altitude, since it impacts the required number of nodes, delay time, and delivery ratio. Moreover, this work is particularly interesting because it takes into account the type of environment (urban, suburban, or rural).

2) HAPs-based solution: HAPs can be either helikites, airships, gliders, or balloons, operating at higher altitudes than LAPs. For instance, in [55], the authors use helikites for deploying 4G-LTE Remote Radio Head (RRH) and providing high capacity Internet services in case of an emergency. Alternatively, other works use balloons in disaster-struck areas (e.g., Google Loon in Puerto Rico) to quickly recover the networks. For instance, the work presented in [56] proposed a novel network of balloons equipped with light fidelity (LiFi) transceivers with a particular focus on the physical design of the platforms. Moreover, the authors in [57] propose an interesting wireless balloon monitoring system, where a high-resolution omnidirectional camera and wireless LAN technologies are exploited to make bird’s eye views available to ground relay stations. On the other hand, Ref. [58] introduces a satellite-aided balloon-based wireless relay system that can be deployed in less than four hours. Besides floating balloons, there is a recent trend of using tethered balloons for enabling connectivity in disaster situations. The authors in [59] presents a comprehensive overview of the characteristics of tethered balloons. More recently, Ref. [60] compared various technologies and promoted the use of WiFi balloon to access social networks in the occurrence of a calamity.

Finally, in [61], the authors tackle important challenges such as routing and resource allocation for heterogeneous vertical networks that include not only HAPs, but also satellites and cell towers. A summary of the papers mentioned in this section can be found in Table II.

C. Using Space Networks

Last but not least, emerging small satellite networks can play a major role in providing connectivity to the disaster struck regions [62]. In this context, several works have considered the use of satellites in disaster situations over the last decade [63]–[69]. For example, authors in [63] introduced the Chinese initiative called LTE-satellite and comprehensively discussed its radio interface technology. Then, in [64], the authors presented an experimental work based on Wideband Internetworking engineering test and Demonstration Satellite (WINDS), showing several examples of satellite-earth station links. Due to the importance of geospatial data for IoT-aided disaster management, Ref. [65] discussed the so-called City Geospatial Dashboard that can be utilized for collecting, sharing, and visualizing geospatial big data, especially helpful in disaster situations.

Other interesting works such as [66] focused on the use of satellites in the context of natural disasters, specifically for weather prediction and warnings for easier evacuation. Finally, [68] discussed multi-mode software-defined radio (SDR) for very small aperture terminal (VSAT) systems as a possible solution to provide cellular coverage in case of large scale disasters, such as the great east Japan earthquake.

III. PHYSICAL LAYER ISSUES

In this section, we survey the main topics related to the physical layer of a post-disaster network. We will mostly
TABLE II
SUMMARY OF THE RELEVANT PAPERS ON WIRELESS TECHNOLOGIES

| Topic                      | Year | Main focus                                                                 | Ref. |
|----------------------------|------|-----------------------------------------------------------------------------|------|
| Recovery of terrestrial networks | 2016 | MDRUs                                                                      | [38] |
|                            | 2017 | Mobile edge infrastructure, cyber-physical systems                          | [57] |
|                            | 2018 | Disaster assessment, data inventory, field situation recording/reporting     | [36] |
|                            | 2019 | D2D and cellular systems                                                   | [34] |
|                            |      | 4G-LTE, D2D, UAVs, MANETs, IoT                                            | [35] |
| Installation of aerial networks | 2013 | Helikites, 4G-LTE RRH                                                      | [55] |
|                            | 2014 | Balloons, monitoring                                                       | [57] |
|                            | 2015 | EVs, UAVs, area partitioning                                               | [41] |
|                            |      | DTN, topology, altitude                                                    | [54] |
|                            |      | Balloons, satellites, relaying, deployment time                            | [58] |
|                            | 2016 | Coverage, relaying, information dissemination                             | [43] |
|                            |      | UAVs, WSNs                                                                 | [39] |
|                            |      | Optimal placement, throughput                                              | [47] |
|                            | 2017 | EANET, AODV, ZRP                                                           | [52] |
|                            | 2018 | Tethered balloons                                                          | [59] |
|                            |      | UAVs, resilience, D2D, power control                                       | [40] |
|                            |      | Implementation of PSO algorithm                                            | [44] |
|                            | 2019 | Trajectory, scheduling, transceiver design                                 | [46] |
|                            |      | Transceiver design, routing, D2D                                           | [51] |
|                            |      | Heterogeneous networks (HetNets), routing, resource allocation             | [61] |
|                            |      | DTN, LoRa                                                                  | [53] |
|                            | 2020 | Cluster localization, UAV path planning                                    | [48] |
|                            |      | Swift communication recovery, time-weighted coverage                       | [49] |
|                            |      | Rate, coverage, D2D                                                        | [50] |
|                            | 2021 | WiFi balloons, social network                                              | [60] |
|                            |      | Deployment, resource allocation                                            | [45] |
|                            |      | Topological aspects, capacity, types of fleets                            | [41] |
| Using space networks       | 2013 | LTE-satellite and radio interface                                          | [63] |
|                            |      | Satellite-gateway links and WINDS                                           | [64] |
|                            |      | SDR-VSAT systems and coverage                                              | [68] |
|                            | 2019 | IoT and big data analytics                                                 | [65] |
|                            |      | Weather prediction and evacuation warning systems                          | [66] |

focus on the differences between the channel models used for terrestrial, aerial, and space communications. However, to the best of our knowledge literature works considering degradation of the environment, for example due to the smoke generated by a wildfire or the debris brought by a tornado, are still missing.

Another important issue that will be covered in this section is related to coverage and capacity in PDCs. These two performance metrics gain great importance in critical situations, since what often saves trapped victims’ lives is being able to access emergency information as well as to share their location to the outer rescuers, which explains why also the problem of localization is included in this section.

A. Channel Models

1) LAPs: Channel modeling is one of the major aspects of post-disaster communication networks, especially when considering vertical heterogeneous networks (VHetNets) since the complexity of the network topology is considerably high. Due to this, the general fading distributions (e.g., Rayleigh, Rician, and Nakagami-\(m\)) are not always applicable in post-disaster scenarios [70]. For example, in [71] we can find an accurate mathematical model allowing us to estimate the ABS’ altitude that maximizes the coverage area and a closed-form expression for computing the line-of-sight (LoS) probability.

Then, the authors in [72] provide a statistical propagation model for predicting the A2G path loss between terrestrial and aerial nodes, given the urbanization level of the environment and the ABS’ elevation angle. In the latter paper, reflections due to objects and trees where neglected for simplicity, while the one due to buildings was modeled under the assumption that their surface was made of concrete, which has considerable dielectric parameters leading to strong reflection phenomena; also, the authors assumed knife-edges in order to evaluate scattering in a deterministic manner, although this implies approximated results.

Furthermore, it should be noted that for urban environments a large percentage of the victims is usually trapped inside buildings with multiple floors, which requires to use a tridimensional (3-D) model. Therefore, Ref. [73] compared the performances of various path loss models as well as the impact of indoor and outdoor environments on both uplink and downlink, which in general are not symmetrical. To model LoS propagation channels usually the Winner II and the free-space pathloss models are used, whereas for the case NLoS propagation the majority of the works relies on Winner II and two-ray models. Hence, the authors in [73] investigated the Winner II pathloss model proposed in [74] with an extra blockage component (which refers to the indoor part of the path), and found it to be the most accurate for urban environments.

Finally, a recent work [70] presented a novel framework to characterize the composite fading channel and optimize both capacity and energy efficiency. In particular, the authors used the Fisher-Snedecor \(F\) distribution to characterize the link between UAVs equipped with intelligent reflective surfaces.
(IRSs) and trapped users, and proved the effectiveness of their resource allocation scheme by means of selected simulation results.

2) HAPs: High-altitude platforms’ characteristics are intermediate between drones and satellites. Their main advantage is probably the long endurance, which implies they could even support PDCs without being deployed after the occurrence of a calamity: HAPs can indeed be aloft for several months, and provide coverage and capacity even in ordinary conditions of the network, meaning that they are not necessarily an ad hoc solution. On the other hand, the time they require for proper deployment might be excessive for most of the emergency situations. To the best of our knowledge, there are no works exclusively focusing on HAPs for PDCs. However, several contributions can be extracted from relevant references with a general validity, such as the following. Ref. [75] assumed a Rician fading channel with K factor for analyzing capacity in HAP networks. The choice of using the Rician fading channel model can be justified by noting that HAPs have a wide elevation angle, which allows them to be almost always in LoS conditions with the typical user within the same cell. Authors in [76] statistically modeled the HAP dual circularly polarized 2 × 2 multiple-input-multiple-output (MIMO) propagation channel and applied the ray tracing approach to the digital relief model to solve the problem of ranging measured data. Furthermore, a theoretical 3-D wideband model was introduced in [77] for HAP-MIMO channel. Note that the tridimensional model was needed because of the considerable altitude of the flying base station, which was assumed to be equipped with multiple transmit and receive antennas aligned in different planes. In the latter work, the Chapman-Kolmogorov equations were applied in order to derive the survival probabilities of scatterers. motivated by the absence of experimental results in the literature, authors in [78] presented a novel statistical channel model of long-distance Ka-band signal transmission via HAP and verified it via numerical simulations. Finally, authors in [79] derived tractable closed-form statistical channel models for ground-to-HAP free-space optical (FSO) links which also take into account the effects of atmospheric turbulence and other relevant aspects of FSO communications.

3) Satellites: For space communications, it is still needed to model the S2G channel because of the current lack of achievable standards. Indeed, even if some standards were established by the Consultative Committee for Space Data Systems (CCSDS), they are often obstructed by technological limitations [80]. The communication link could leverage either laser, RF, or VLC. The critical aspect to take into account is the energy consumption for each technique, since satellites essentially rely on solar energy.

The signal envelope is subjected to three main sources of variation, namely multipath fading, LoS shadowing, and multiplicative shadow fading. The first one, which is usually modeled by Rayleigh or Rice distributions, is generated by the combination of all the scattered NLoS components along with a possible LOS ray, leading to rapid small-scale fluctuations. On the other hand, LoS shadowing arises from a LoS obstruction due to objects (e.g., trees and buildings), which implies slower fluctuations on a larger scale. Finally, the multiplicative shadow fading phenomenon is responsible for random variations in the power of LoS multipath components. Most of the famous models consider land-mobile-satellite communication systems, and can be categorized as static (e.g., the ones developed by Loo [81], Corazza-Vatalaro [82], Hwang [83], Patzold [84], Kourogiorgas [85], Abdi [86], and Saunders [87]) or dynamic (e.g., the ones developed by Fontan [88], Scalise [89], Nikolaidis [90], and Lopez-Salamanca [91]). Authors in [92] considered a dual-polarized MIMO channel, focusing on the models referred to as \textit{Quasi Deterministic Radio channel Generator} (QuaDRiGa) and Loo in order to capture the ionospheric, tropospheric, and fading effects on a land mobile satellite (LMS) system. In the same context, authors in [93] introduced an algorithm for modeling dual-polarized MIMO channel while taking into account LoS shadowing, multipath effect, elevation angle, and other relevant channel factors. Ref. [94] introduced a reliable channel model for taking into account dynamic cloudy weather impairments, which impact on the Rician factor and signal propagation. On the other side, a simplified fading channel model for describing received signals, multipath fading, and shadowing effect has been analyzed by the authors of Ref. [95]. In [96], instead, the so-called channel reservation strategy is promoted as a solution for improving access and handover performances. Finally, authors in [97] presented an original channel model for 5G and beyond which, based on atmospheric data, allows to predict channel attenuation at any time.

B. Coverage and Capacity

1) Coverage: In typical post-disaster scenarios, D2D communication along with UAVs can be used to provide ubiquitous coverage. Most of the existing works focus on using D2D for communicating in lack of a functioning infrastructure [46], [98]–[101]. For instance, authors in [98] have proposed an LTE-based D2D technology and evaluated its performances for a typical disaster scenario. Authors in [46], instead, have proposed establishing multihop D2D links to extend the coverage area of UAVs when there is a lack of functioning cell towers. Furthermore, Ref. [99] suggests a hierarchical D2D channel model that accounts for the mobility of users and the availability of communication resources. Table III summarizes the relevant papers on channel models.

| Topic   | Year | Main focus                              | Ref. |
|---------|------|-----------------------------------------|------|
| LAPs    | 2014 | Altitude, LoS probability                | [74] |
|         | 2018 | Resilience                              | [40] |
|         | 2021 | Power allocation                        | [70] |
| HAPs    | 2017 | Rician fading channel, capacity         | [75] |
|         | 2020 | Ka-band transmission                     | [78] |
| Satellites | 2014 | Rician factor, signal propagation       | [94] |
|         | 2016 | Fading channel                          | [95] |
|         | 2017 | Dual-polarized MIMO, LMS                | [92], [93] |
|         | 2019 | Channel reservation strategy, handover  | [96] |
|         | 2020 | Channel attenuation                     | [97] |
architecture with a centralized SDN controller communicating with the cloud head to minimize energy consumption. Also, authors in [100] suggested deploying UAVs to discover D2D devices in disaster-struck regions. Finally, authors in [101] provided an overview of the use of ubiquitous mobile devices and applications in the context of 5G for post-disaster communications. Ref. [34], instead, proposed to combine D2D and cellular technologies to improve the coverage probability. The work proposed in [49] introduced a performance metric called time-weighted coverage (since the behavior of the network is dynamic) to promote a novel 3-D networking architecture with both terrestrial and aerial nodes. The concept of coverage has also been discussed in [51] since UAVs are proposed as an effective solution to make up for the eventual loss of coverage for IoT applications. Authors in [102] studied via simulations the optimal deployment of wireless gateways and relay nodes while considering its influence on field commanders’ positions.

2) Capacity: Whenever there is a failure in the network infrastructure, not only coverage but also capacity becomes a critical issue. This is the entire load has to be divided among only the surviving BSs, leading to outages and low data rates. Also for this topic, very few relevant research articles have been published recently and are mentioned in what follows. In [41], the deployment of the best aerial fleet in order to maximize the capacity in the middle of the disaster-struck area has been investigated. Ref. [67], instead, included design considerations for a capacity-oriented LEO satellite constellation and implemented a multi-objective genetic algorithm that optimizes a combination of constellation cost, capacity, and multiple-coverage.

C. Case Studies Related to Coverage

In this part, we present two simulation setups to extract valuable insights about some of the aspects discussed before, including terrestrial and aerial ad hoc platforms, satellites, and especially the size of the disaster. Both setups assume uniformly distributed users and TBSs; however, inside the disaster area $A_0$ (assumed circular with radius $r_d$), the original infrastructure is nonfunctional, while outside, it operates appropriately with a reliable connection to the core network (e.g., utilizing optical fiber links). The QoS is evaluated based on averaged coverage probability experienced by the users inside the suffered region. A summary of the main system parameters is presented in Table V, where $h$ denotes the transceiver altitude and the subscripts $L$, $H$, $M$, $T$, and $S$ respectively refer to LAPS, HAPS, MDRUs, TBSs, and LEO satellites.

1) First Setup – Small Disasters: In this case, we assume that $r_d$ is relatively small (i.e., from a hundred meters to ten kilometers), and thus LAPS are generally preferred over HAPS [41]. As depicted in Fig. 4, we propose a simple strategy that consists in deploying one single LAP above the disaster epicenter as well as a set of MDRUs (BPP-distributed over the disaster area).

Therefore, the users can associate with any of the three types of BS (outer TBS, LAP, or MDRU), but only TBSs are directly connected to the core network. Hence, if the user associates themselves with a LAP or an MDRU, one wireless backhaul link will be needed. Based on the maximum average received power association rule for each consecutive link and assuming MDRUs to have only access functionalities, the possible paths are user–TBS, user–LAP, user–LAP–TBS, user–MDRU–TBS, and user–MDRU–LAP–TBS.

The results displayed in Fig. 5 clearly show that the coverage probability strongly depends on $r_d$, and in particular, a larger disaster radius generally implies a lower QoS. Indeed, for large values of $r_d$ the system suffers the fact that, given that the distance to the closest TBS often is larger than the respective coverage radius, one single drone is not sufficient to provide reliable backhaul for hundreds of MDRUs. Therefore, the backhaul link becomes the bottleneck of the system.

Moving to more specific considerations, the simulated curves define two different cases:

(i) As long as $r_d$ does not exceed one kilometer (see the blue and the red lines), MDRUs are unnecessary since the user can easily associate to either the LAP or the closest TBS;

(ii) For much larger disasters (see the yellow lines), the optimal

| Topic | Year | Main focus | Ref. |
|-------|------|------------|------|
| Coverage | 2015 | Optimal deployment, wireless gateways, relay nodes | [101] |
| | 2015 | D2D, SDR | [99] |
| | 2017 | D2D, SDN | [100] |
| | 2017 | D2D, UAVs | [100] |
| | 2018 | D2D, LTE | [98] |
| | 2019 | D2D, multihop, UAVs | [48] |
| | 2020 | D2D, 5G, UAVs, IoT | [51] |
| | 2020 | Time-weighted coverage, HetNets | [49] |

| Capacity | 2020 | Satellites, cost, multiple-coverage | [67] |
| 2021 | ViHetNets | [41] |

| Description | Value |
|-------------|-------|
| Number of system realizations | $2 \times 10^4$ |
| Simulation radius | $r_s = r_d + 3$ [km], for TBSs $h_T$, for satellites |
| Type of environment | Urban [71] |
| TBS density | $\lambda_T = 10$ TBS/km$^2$ |
| Path loss exponents | $\alpha_M = 3$, $\alpha_T = 2.9$, $\alpha_L = [2.5, 3]$, for [Los, NLoS] $\alpha_H = [2.2, 3]$, for [Los, NLoS] $\alpha_S = 2$ |
| LAP altitude | $h_L = 0.2$ km |
| Transmit powers | $p_T = p_M = 10$ W $p_L = 3$ W $p_H = 20$ W $p_S = 1000$ W |
| Nakagami-m shape parameters | $m_T = m_M = 1$ $m_L = 2$ $m_H = m_S = 3$ |
| SINR thresholds | $\gamma = 0.1$, for access links $0.2$, for backhaul links |
| Noise power spectral density | $\sigma_n^2 = 10^{-12}$ W/Hz |

| Table IV | Summary of the relevant papers on coverage and capacity |
|----------|------------------------------------------------|
| Topic | Year | Main focus | Ref. |
| Coverage | 2015 | Optimal deployment, wireless gateways, relay nodes | [101] |
| | 2015 | D2D, SDR | [99] |
| | 2017 | D2D, SDN | [100] |
| | 2017 | D2D, UAVs | [100] |
| | 2018 | D2D, LTE | [98] |
| | 2019 | D2D, multihop, UAVs | [48] |
| | 2020 | D2D, 5G, UAVs, IoT | [51] |
| | 2020 | Time-weighted coverage, HetNets | [49] |

| Capacity | 2020 | Satellites, cost, multiple-coverage | [67] |
| 2021 | ViHetNets | [41] |

| Table V | Main simulation parameters |
|----------|---------------------------|
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| Type of environment | Urban [71] |
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| Path loss exponents | $\alpha_M = 3$, $\alpha_T = 2.9$, $\alpha_L = [2.5, 3]$, for [Los, NLoS] $\alpha_H = [2.2, 3]$, for [Los, NLoS] $\alpha_S = 2$ |
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| Transmit powers | $p_T = p_M = 10$ W $p_L = 3$ W $p_H = 20$ W $p_S = 1000$ W |
| Nakagami-m shape parameters | $m_T = m_M = 1$ $m_L = 2$ $m_H = m_S = 3$ |
| SINR thresholds | $\gamma = 0.1$, for access links $0.2$, for backhaul links |
| Noise power spectral density | $\sigma_n^2 = 10^{-12}$ W/Hz |
number of MDRUs \( (n_M^*) \) jumps to several hundreds, since average distance between the user and either the LAP or the closest surviving TBS becomes excessive;

(iii) The value of \( n_M^* \) always increases as \( r_d \) increases. Moreover, if \( r_d \) is sufficiently small, the presence of a LAP reduces \( n_M^* \) since a considerable percentage of users directly associates to the aerial node and does not need further MDRUs; on the other hand, for \( r_d = 10 \) km the backhaul link offered by the LAP becomes vital and promotes the deployment of further ad hoc nodes, which otherwise would mostly backfire because of their limitations in reaching the core network.

a) Second Setup – Large Disasters: The simulation results regarding first setup have evidently shown the limitations of the proposed strategy when \( r_d \) exceeds a few kilometers. Therefore, we hereby test a different network architecture that supports the surviving infrastructure by means of a HAP above the disaster epicenter and a LEO satellite (see Fig. 6). For the HAP-satellite link, the shadowed Rician fading channel is assumed according to [103].

For this setup, we assume that the satellite backhaul connection to the closest ground station is ideal. However, the user can exploit the satellite only for backhaul, by associating to a HAP. Therefore, the set of possible communication paths consists of just three elements: user–TBS, user–HAP–TBS, and user–HAP–satellite.

We can note that Fig. 7 is consistent with Fig. 5, meaning that, for \( r_d = [1, 10] \) km, the blue curve in the former matches with the initial values of the respective dotted lines in the latter. Moreover, several insights can be extracted:

- It is evident that the satellite altitude \( h_S \) does not have a considerable influence on the coverage probability (the yellow and red markers match with the respective solid lines). This suggests that, for any value of \( r_d \), the air-to-space backhaul link is not the bottleneck of the system;
- Despite its altitude is not relevant, the satellite starts playing a vital role as \( r_d \) exceeds a dozen kilometers;
- For \( r_d \to 1 \) km, the proposed scheme cannot provide a strong support to the terrestrial infrastructure (i.e., the coverage probability falls between 40% and 60%, no matter which of the proposed strategies is implemented);
- For any value of \( r_d \), the highest QoS can be achieved when a satellite is available and the HAP is deployed at relatively low altitude, despite the lower LoS probability.
Fig. 6. Proposed system setup for large disasters: one HAP hovering above the origin $O$ and one satellite around the area of interest support the disaster-struck terrestrial infrastructure.

Fig. 7. Simulated coverage probability for the second setup ($n$ denotes the number of nodes).

D. Radio Resource Management

Spectrum allocation is a crucial aspect of emergency management systems (EMSs). For instance, [35] discussed spectrum allocation strategies and future technologies for EMSs. Ref. [104] introduced aerial network access and resource allocation scheme that optimizes the number of human portable/wearable machine-type devices (HMTDs) that are transmitting data. In the same context, authors in [105] proposed a radio resource management system based on orthogonal frequency-division multiplexing (OFDM) using a novel resource allocation technique for improving aerial networks’ data communications. Moreover, in [106], a novel 5G network architecture based on slicing is introduced for supporting first responders’ (FRs’) communications by dynamically prioritizing their channels, depending on their need. The authors of Ref. [107], instead, investigated the use of radio access network (RAN) slicing and introduced management mechanisms that allow handling the slice reconfigurations. For aerial networks, an autonomous spectrum management scheme based on spectrum sharing has been introduced and validated via simulation results in [108]. Finally, authors in [109] proposed a resource allocation scheme for UAV-enabled cellular networks as well as efficient algorithms for clustering selection and resource allocation.

E. Localization

Humans affected by a disaster must be rescued within the so-called golden 72 hours after the disaster. In this context,
localization plays a major role in emergency scenarios, especially if for the trapped victims. Ref. [110] provided an insightful overview of the existing localization algorithms for post-disaster scenarios using WSNs. The authors in [111] proposed one possible approach for localizing damages and humans in a disaster-struck region. Alternatively, authors in [112] introduced a modeling and simulation method of the radio channel for rescue purposes, which can be used to develop radio localization systems. In general, the passive localization schemes that are developed in various works can be applied to post-disaster situations. For instance, [113] discusses localization in a WSN for different applications. In the same context, authors in [114] implemented their algorithm by using particle swarm optimization (PSO) and promoted the path planning strategy based on a grid scan.

Generally speaking, localization techniques can be categorized as centralized (if the input data are processed by the BS) or decentralized (if the input data are processed by the sensor nodes) [115]. Due to the susceptibility of cell towers as well as the limited availability of power in disaster circumstances, our interest is mostly oriented towards decentralized localization techniques which can be further distinguished as range-based and range-free techniques. Range based techniques require accurate measures of distances or angles between the devices of the network, and therefore they require an additional hardware as well as a stronger power supply when compared to range-free techniques [116], which however are usually less precise. Authors in [117] introduced a range-free scheme for localization in WSNs, which makes use of fuzzy logic to relate the received signal strength (RSS) and the distance so that the location can be evaluated in sufficiently precise manner. Following the same lines, the process of localization and the related procedures were presented in [116] together with the taxonomy of range-free techniques, with a special focus on the so-called DV-HOP algorithm. Furthermore, Ref. [118] implemented two WSN-based methods to ensure the localization of vibration damage in tunnels. Finally, authors in [119] focused on the estimation of both position and transmission orientation of a directional source in 3-D WSNs.

F. Energy Efficiency

Since the power infrastructure is also susceptible to calamities, highly energy efficient systems are extremely important in emergency circumstances [36], [44], [45], [120]–[130]. For example, Ref. [120] proposed a disaster-time system that makes use of a message ferry method to collect and exchange information while improving DTNs’ energy efficiency; in particular, the authors introduced a method that allows to relay the messages of mobile terminals with low battery level to the terminals with higher battery level, avoiding the former to fully discharge. Inspired by biological networks of living organisms, the authors in [121] introduced an energy-efficient disaster response network (DRN), called Bio-DRN, modeled via an integer linear programming optimization problem. In the same work, the Bio-DRN was developed by means of a sub-optimal heuristics and tested via simulation considering a real disaster-prone region in Nepal.

Authors in [122] investigated the possibility of mounting solar panels on top of UAVs to increase their autonomy while taking into account routing, data rate, and transmit power constraints. Evidently, the main issue with this solution is represented by the additional payload due to the panels themselves. On the other hand, authors in [123] promoted a heterogeneous fleet that includes untethered drones for cellular coverage, tethered drones for high-capacity backhauling, and untethered powering drones for charging. In [124] a novel beamforming architecture, based on conditional time split-energy extraction (CT-EE) for enhancing nodes’ autonomy, was presented and compared to conventional beamforming and other energy extraction methods.

Furthermore, to minimize both message overhead and energy consumption, [125] proposed a hybrid solution for DTNs where the routing protocol is chosen depending on the mobility patterns of each node. Works such as [126], instead, focused more on optimizing data traffic throughput. In particular, the authors described the problem via mixed integer linear programming (MILP) and developed a traffic demand-aware off-line energy-efficient scheme for WMNs constituted by renewable-energy-enabled base stations (REBSs). Moreover, in the context of WSNs for disaster monitoring, Ref. [127] presented an energy-efficient data retrieval scheme based on intelligent sleep scheduling. In addition, the authors mathematically proved that the proposed scheme is capable to extend the longevity of the network, while contributing with traffic reduction and load balancing. An interesting problem tackled with stochastic geometry is [128]. Here, the authors used energy harvesting and transfer for the user equipment in D2D clustering communications for disaster management; the required power would be captured from RF signal via BS. The novelty of the work presented in [129], instead, consists in combining both spectrum and energy efficiencies (thus, a new metric called spectrum-energy efficiency was defined) for renewable-energy-enabled gateways and MDUs deployed in disaster struck environments. In particular, the authors proposed a topological scheme based on the top $k$ spectrum-efficient paths and showed how to optimize the value of $k$ itself. Finally, authors in [130] developed an algorithm for network reconfiguration in underwater communication systems that are capable of harvesting energy in case of disasters occurring in the ocean, such as tsunamis.
TABLE VIII
SUMMARY OF THE RELEVANT PAPERS ON ENERGY EFFICIENCY

| Year | Main focus | Ref. |
|------|------------|------|
| 2014 | MDRU, spectrum efficiency | [129] |
| 2015 | Mobility, DTN protocols | [125] |
| 2018 | Energy harvesting, D2D | [128] |
| 2019 | Temporary communication system, DTN | [120] |
| 2020 | Solar powered UAVs | [122] |
| 2021 | Data retrieval | [127] |

IV. NETWORKING LAYER ISSUES

Together with the physical layer, the networking layer is critical in PDCs. In this section we survey various related aspects, including as space-air-ground integrated networking (from its architecture to its inherent complications), the proposed routing algorithms specifically designed for PDCs, and the applications of DTNs and edge computing in emergency scenarios.

A. Integrated Space-Air-Ground Architecture for PDCs

Space-air-ground integrated network (SAGIN) is an emerging architecture that can be also used in post-disaster scenarios. The main idea behind this solution is to conveniently combine the three layers: in fact, terrestrial networks have the lowest delays and the highest capacity (often without energy constraints), while satellites benefit from an extremely wide coverage area and they are generally resilient to any disaster; aerial platforms, instead, have intermediate characteristics between terrestrial and space nodes. For this paradigm, the space, air, and ground segments can either inter-operate or be independent of each other. One typical example of SAGIN architecture is the so-called Global Information Grid (GIG), which is made by four layers (i.e., ground, aerospace, near-space and satellite layers) embedding the communication, sensor, and operation networks [131]. Generally speaking, the space network may include geosynchronous equatorial orbit (GEO), medium Earth orbit (MEO), and LEO satellites, with the respective terrestrial infrastructures (e.g., ground stations and control centers). Note also that the terrestrial layer is not limited to cell towers, but may also include MANETs, wireless local area networks (WLANs), etc.

In Ref. [132], a novel cooperative communication scheme for UAV-aided satellite/terrestrial integrated mobile communication systems (STICSs) is proposed as a means of interference mitigation. Indeed, the UAVs act as relay stations and, according to the simulation results obtained, allow to reduce the average bit error rate (BER) and boost the throughput of the system. Authors in [133], on the other side, provided a framework for using Internet Protocol (IP) for disaster management services within a SAGIN. The study simulated two disasters occurring in Africa and North America, and showcased the additional services offered by the proposed IP-based method.

B. Routing

Since optimizing routing in disaster scenarios can tremendously improve the performances of the network (especially in terms of energy efficiency and delay), several works have recently tackled this topic. For instance, [134] has improved the multicast routing squirrel search algorithm (SSA) for providing green communications and has experimentally shown the effectiveness of properly balancing energy consumption and other QoS parameters. The study proposed in [135], instead, relied on real-world maps and suggested several methods on access point placement and routing in order to quickly connect users inside middle-size disasters. Moreover, authors in [136] proposed a D2D-based framework to cluster users’ devices and optimize the transmission power for each gateway. One of the most remarkable strategies consists in putting the nodes within the damaged area in LISTEN mode and provide them the clustering instructions from a functional area, thus saving valuable energy to the devices.

In the context of dual-channel-based MANETs, authors in [137] recently introduced an algorithm for efficient routing, since each node is able to configure the routing table based on the exchanged neighbor list. The main application suggested for this work is indoor communications for firefighters, especially since previous works do not consider the mobility of the nodes properly, and neglect the presence of potential obstacles in the environment. Another approach based on routing table has been proposed in [138], where the concept of intercontact routing was introduced to estimate delivery probabilities and route delays, as well as to find reliable routes and consequently control message replication and forwarding. Furthermore, the authors enhanced the energy efficiency of protocol by means of a differentiated message delivery service.

For UAV networks, instead, Ref. [139] suggested a location-aided delay-tolerant routing (LADTR) protocol in order to exploit both store-carry-forward (SCF) technique and location-aided forwarding. Indeed, this work improved the efficiency of SCF by introducing ferrying UAVs into the network, and validated the LADTR protocol by numerically comparing it (in terms of routing overhead, packet delivery ratio, and average delay) with other common protocols.

Authors in [140] focused on DTNs and introduced additional routing methods (e.g., Node Selection by the evacuator’s territory, Data Triage by data priority, and Dynamic FEC controls by the Jolly-Sobor model). In this work, field experiments were carried out for validating the performances of the proposed routing methods. Moreover, the authors of Ref. [125] suggested hybrid DTN protocols for allowing nodes to apply different routing rules depending on their own mobility patterns. Instead, authors in [141] introduced and analyzed a DTN routing protocol for information-centric networks (ICNs) in disaster-struck areas, showing its advantages in terms of delivery probability and overhead ratio. Finally, the D2D-based architecture proposed in [99] uses a SDN controller which can conveniently enable multi-hop routing path between victims and FRs.
C. DTNs and SDNs

Whenever there is no way to ensure a reliable backhaul link to the core network, there is a risk of suffering from relatively long delays. Since this situation is recurrent in emergency scenarios, DTNs can play a crucial role in the context of disaster management. Therefore, many researchers started investigating the potential applications of DTNs in this area. In this subsection we comment on the works that, according to our opinion, are the most relevant for this topic.

Authors in [12] proposed a four-layer architecture consisting of a combination of SDN and DTN in order to minimize packet loss. Interestingly, the Mininet-WiFi simulation results suggested that the proposed architecture can achieve a packet loss as low as 0.46%. In [142], instead, the so-called IBR-DTN architecture (i.e., an implementation of the bundle protocol RFC5050) has been shown to be effective when sending small size data such as text messages. On the other side, if the connection is lost during the transmission then the entire file would need to be sent again, which makes this architecture very inefficient for sending heavy files. Ref. [143] has suggested to use delay-tolerant networking in a location-based mobility prediction scheme that estimates the mobility pattern of the nodes (e.g., first responders or victims equipped with smart devices) and enables to select the best forwarder. Another interesting work has been presented in [144], where the authors promoted an infrastructure-less health data delivery process architecture capable of automatically identify injured persons. In order to make up for the eventual unavailability of cloud-based mapping services and data in post-disaster scenarios, authors in [145] have presented DTN MapEx: a distributed computing system that generates and shares maps over a DTN. To do this, users need to log the GPS traces of their routes and collect data about the disaster-struck environment; then, pre-deployed computing nodes process the collected data to generate a map for the network. Ref. [146] devised a novel DTN-based message relay protocol that incorporates message delivery into a specific type of shelter network called autonomous wireless network construction package with intelligence (ANPI). This solution was tested via simulations, showing its effectiveness in reducing redundant transmissions and improving the message delivery ratio.

The authors in [147] derived a principal component regression model and proposed an opportunistic demand sharing scheme for collecting and spreading resource demands to the control station via a smartphone-enabled DTN. By means of selected case studies, this work also illustrated to what extent DTNs can be useful for demand forecasting. More recently, the concept of DTN has been applied also for post-disaster resource allocation, used in a novel opportunistic knowledge sharing approach for gathering the resource needs in a utility-driven system [148]; simulations results showed that the proposed system is very competitive with the similar ones proposed in literature, especially in a fully connected scenario. Finally, Ref. [149] used realistic traffic and mobility data in order to evaluate various routing schemes for DTNs, and introduced the option of combining dedicated DTN routing to additional aerial nodes.

D. Edge Computing

By definition, edge computing is an autonomous computing model that comprises many distributed devices communicating with the network for several computing tasks [150]. In other words, edge computing is a paradigm meant to move computational data, applications, and services from the cloud servers to the edge network to minimize latency and maximize bandwidth [151].

Edge computing can be of valuable in disaster situations, primarily due to providing low latency. For instance, [152] devised Echo, an interesting edge-enabled framework for disaster rescue, relying on computer vision to analyze and filter crowdsourced pictures to provide only relevant content to FRs and preserve bandwidth. The authors also designed an adaptive photo detector to improve the precision and recall rate. On the other hand, authors in [153] recently implemented mobile edge computing (MEC) task management strategies by applying long-range wide-area networking (LoRaWAN) to UAV-aided architectures. The presented simulation results promoted this solution since it conveniently enables long-range MEC service. Then, authors in [154] proposed a data backup scheme to combine edge computing and blockchain technologies for disaster scenarios: while the former processes big data coming from the microgrid, blockchain provides security to the equipment needed to perform edge computing. However, the main challenge here is to deal with the trade-off between energy efficiency and security. Moreover, the authors in [155] designed and implemented a named-data-networking-based support system over the edge computing platform KubeEdge. By doing this, this work showed the effectiveness of the proposed solution in promoting efficient emergency communications and responders’ mobility. Finally,
authors in [156] studied resource allocation to enable latency-intolerant tasks due to emergencies in oil fields. In particular, they devised a stochastic model that captures end-to-end uncertainties within the proposed federated edge environment to estimate the risk associated with each task and showed a performance improvement of almost 30 percent compared to state-of-the-art solutions.

V. CHALLENGES AND RESEARCH DIRECTIONS

Despite the research efforts discussed in the previous sections, there are still many open problems to address. In particular, this section focuses on modulation and coding schemes, backhauling, optimal placement and trajectory/scheduling, and handover issues while suggesting possible future research directions.

A. Modulation and coding schemes

In our vision, another crucial aspect for studying the physical layer in PDCs regards the modulation and coding schemes to use. Unfortunately, this area has not been strongly tackled by recent works\(^2\), but nonetheless insightful considerations have been presented for general applications. For instance, Ref. [157] presents a secure and inexpensive gossiping method enabled by reinforcement learning and game theory to mitigate the communication losses usually occurring in disaster scenarios. Simulation experiments validated the benefits of this approach, compared to other schemes from the literature, in terms of overhead, latency, reliability, security, and energy efficiency. Furthermore, [56] presented the derivation of the mean co-channel interference for one-dimensional and bidimensional LiFi balloon networks (LiBNets) that are distributed according to a homogeneous Poisson point process (HPPP). Finally, the work presented in [69] is a study about the mixed support of time division multiple access (TDMA) and single channel per carrier (SCPC) transmission for improving the bandwidth utilization in satellite-aided disaster communications. The authors considered four different scenarios in order to categorize the formation of bandwidth assignment depending on the network’s characteristics.

B. Backhauling

One crucial functionality of cell towers is providing backhaul connections to mobile users. Most of the ad-hoc solutions discussed above provide access only, meaning they still have to rely on terrestrial BSs (TBSs) for backhaul connectivity. To this extent, novel solutions are needed to make up for the potential failure of TBSs by ensuring reliable backhaul links for any other node of the network.

Motivated by the frequent catastrophes that occurred in the Philippines, Ref. [158] devised a solution to provide GSM access and backhaul in the aftermath of a disaster. The idea is essentially to rapidly deploy a mini-cell tower and make it operate in IP protocol (e.g., via TVWS or WiFi backhaul links) to serve first responders and victims. Then, [159] suggested using worldwide interoperability for microwave access (WiMAX) technology to serve as backhaul to the WiFi network in disaster recovery circumstances by integrating it with WLAN access points. In addition, the authors implemented voice over IP (VoIP) services in order to assess the system’s capabilities. Moreover, [160] recently borrowed tools from stochastic geometry to estimate the effectiveness of millimeter wave (mmWave) backhauling for ABS-aided terrestrial networks. In particular, an algorithm was developed to maximize the throughput based on user association, UAV positioning, and resource allocation. Furthermore, [161] jointly optimized resource allocation, user association, and UAV positioning while taking into account both access and backhaul links, since the transmission rate of the system is given by the minimum between access and backhaul transmission rates.

One of the main backhauling problems in post-disaster situations is to maximize the reliability of backhaul links, which requires perfect aligning between the transmit and receive antennas, given that mmWave systems are known for their high directivity. In the context of emergency communications, splitting access and backhaul resources might be convenient since dynamic algorithms can be used to adapt the network depending on the different phases of disaster management; also, proper transmit power allocation combined with spatial multiplexing can mitigate interference from the user side. However, accurate beam steering error models still need to be investigated and, since UAVs are also used as relays without any queuing capabilities, it also would be interesting to analyze spatio-temporal models with queuing for the ABSs [160].

Apart from intelligent allocation of resources such as bandwidth and energy [162], backhaul links also require proper deployment of the network nodes in order to be reliable and effective. Usually, heterogeneous networks have higher complexity; meshed networks might be more convenient in emergency scenarios due to their higher level of redundancy and versatility. However, the inherent challenge in deploying large scale self-organizing networks with UAVs is that the topology is subject to continuous modifications, and thus fast computational methods are needed for management. To this extent we think that, whenever their implementation is feasible, tethered backhaul UAVs [123], [163] generally represent a good solution to the problem.

C. Optimal Placement

Given the increasing interest in vertical heterogeneous networks and their utility in post-disaster scenarios, it is essential to consider the optimal placement of ABSs because higher mobility and relocation flexibility characterize aerial nodes differently compared to their terrestrial counterparts. This,
in turn, brings the opportunity to optimize the aerial nodes’ locations to obtain the best network’s performance either in terms of coverage, capacity, or energy efficiency (or any combination of the three).

For instance, [164] devised an analytical model describing how survivors can place (by means of a step-by-step guide in the form of mobile application) relay nodes such as mobile phones to communicate over long distances. However, the main challenge is to improve the analytical model since it can only describe the trend of the channel quality and it is generally impractical to perform measurements in emergency scenarios. Moreover, Ref. [165] borrowed tools from optimization theory to determine how to place edge-devices (i.e., where and how many) to conveniently provide reliable connectivity to FRs.

In the context of aerial networks, the choice of optimal placement of the ABS can be based on the study of several characteristics of the environment (e.g., shape and size of the disaster area, QoR of the terrestrial network, load distribution, etc.) [41]. Knowing such information makes it possible to minimize the aggregate interference and maximize the QoS for both the FRs and the victims involved in the disaster. Therefore, the main challenges for successful deployment of ABSs are mostly related to assessing the topology of the environment itself, which may require a relatively long time, and the estimation of the channel, which strongly affects the effect of each transmission on the user experience. Hence, novel and efficient methods and algorithms need to be devised to solve these issues. The study presented in [166] focused on the impact of various parameters, such as the size of the recovery area, the altitude and the number of nodes per cluster, and the transmit power for backhaul on ABSs, while the authors in [46] discussed the optimal hovering positions of UAVs-based relaying systems. Moreover, works such as [47] and [123] have quantitatively shown that how optimal placement of ABSs can contribute in terms of throughput enhancement. Finally, [167] optimizes the positions of ABSs and the assigned users to maximize spectral efficiency while keeping a sufficient QoS for the users. However, as the authors remarked, even assuming to solve the problem of positioning the UAVs, other challenges still need to be overcome, such as achieving sufficient self-organizing network capabilities, and mitigating the co-channel interference due to the high percentage of LoS aerial links. Moreover, developing effective trajectory planning and control mechanisms is required in order to deal with the high mobility demands, as we will discuss in the following subsection.

D. Optimal Trajectory and Scheduling

Trajectory planning is critical when deploying ABSs, especially those characterized by fixed wings because they cannot simply stay aloft in a specified position. Therefore, the location of the aerial nodes should be adjusted in real-time, in order to avoid collisions or follow the movement of the load (e.g., users escaping from a building on fire and moving towards a shelter). In this context, works such as [46] optimized UAVs’ trajectory and scheduling to connect ground devices and surviving BSs in the most effective way. Then, [168] recently studied the influence of obstacles on the status of road networks and the speed of rescue vehicles to generate effective safe routes for FRs. In this work, the authors mentioned several challenges to be overcome in the future, for example: (i) extending the framework to the case with multiple vehicles and destinations; (ii) developing a routing algorithm that takes into account not only the risks associated to routes, but also FRs’ time constraints; (iii) developing a user interface that allows to adapt the routing parameters based on real situations. Instead, [169] presented swarm-intelligence-based localization and clustering algorithms for trajectory optimization in aerial emergency networks. According to the authors, the next step would be to investigate bio-inspired AI techniques to improve the performances of the algorithms. Another interesting work, presented in Ref. [100], aims to optimize the UAV flying paths, in terms of both coverage area and energy efficiency, depending on the type of disaster (e.g., earthquake, flood, wildfire, etc.). In addition, an extensive comparison between the S-, O-, ZigZag-, and rectangular paths was discussed by the authors.

Finally, further considerations for UAV trajectory optimization are available in [40]. Nevertheless, the research on optimizing ABSs’ trajectory and scheduling for post-disaster networks is still in its infancy and needs further investigation. One possible direction in this domain consists in developing powerful distributed algorithms that can identify optimal trajectories for a fleet of UAVs (which can be needed in case of large disasters or high capacity needs) and a team of FRs or a group of victims that need to be rescued.

E. Handover Management

Another major challenge in PDCs is the handover management between the ABSs, especially in terms of handover cost (i.e., the fraction of time that, on average, is spent for
TABLE XIV

| Topic                        | Year | Main Focus                              | Ref. |
|------------------------------|------|-----------------------------------------|------|
| Trajectory, scheduling       | 2019 | Resilience, UAVs                        | [46] |
| Trajectory                   | 2017 | Coverage, energy efficiency             | [100]|
|                              | 2018 | Optimization techniques                 | [40] |
|                              | 2019 | Localization                            | [169]|
|                              | 2020 | Road networks                           | [168]|

associating with another ABS). Note that for the case of aerial networks, this does not depend only on the user’s velocity but also on the speed of the aerial nodes since, as extensively discussed in the previous subsection, they are usually non-stationary.

The research works on handover management for ABSs is sparse and, to the best of the author’s knowledge, only [170] investigated the rate performance of a UAV-aided three-tier downlink network by taking into account the effect of handover rates on the user rate. In particular, [170] assumed two operating modes, namely conventional (where all the BSs transmit data and control signals) and control/data split (where only UAVs provide control signals but any BS can provide the data), showing that the latter generally reduces the handover cost. To this extent, designing efficient handover schemes for integrated terrestrial-vertical heterogeneous networks becomes very challenging. For a given situation, the main problem is, indeed, to understand the optimal density of nodes so that the handover rate remains acceptable.

F. Content Caching

Content caching is an emerging area for data distribution where the content is provided to the user from the closest servers [171]. In general, the benefits provided by edge caching are the following: (i) edge nodes placed close to the users can cache popular contents to reduce both the delay and the load experienced by the BSs, and (ii) traffic through backhaul links is minimized since redundant data transmissions are avoided [172]. In this context, [172] proposes an effective and secure caching scheme for ensuring backup in case of disasters. This scheme was designed to serve mobile users in mobile social networks (MSNs) with fog computing (i.e., one of the main aspects of edge computing) and secure encryption. We also recall that, in the context of disaster evacuation, a recent review on fog computing can be found in [16].

Instead, authors in [173] used edge caching, where a generic multiple UAV-enabled radio access network (UAV-RAN) is utilized for spectral efficiency enhancement. In particular, they assumed a stochastic geometry-based setup and suggested dividing the caching contents into two sets with different ranges of popularity: the most popular files would be stored at all ABSs, while the least ones just at one ABS. The optimization problem consists in finding the proper popularity threshold to define the two sets, and the authors derived the expression of the threshold based on Fenchel duality. One major challenge for using content caching in post-disaster situations is optimizing content distribution in cloud servers to reduce costs, latency, and resource consumption.

VI. Conclusions

In this paper, we surveyed recent works on the development of post-disaster wireless communication networks, which are envisioned as one of the most relevant aspects of 5G and beyond connectivity. We showed that current research is highly focused on developing novel algorithms, technologies, and architectures to improve the overall network performances in case of emergency. Moreover, we discussed the main challenges and limitations these studies face and linked them to future research directions, as well as the need to carry on practical experiments and field tests. Mainly, we provided an overview of the existing literature works, by investigating the general procedures and strategies for counteracting any large-scale disasters and the possible technological solutions for post-disaster communications, such as the recovery of the terrestrial infrastructure, installing aerial networks, and using spaceborne networks. Finally, by numerical evaluation of the coverage probability of the network in realistic post-disaster scenarios, we proved the effectiveness of creating novel ad hoc architectures that properly combine existing wireless technologies. Therefore, by discussing relevant literature works, novel case studies, and current technological challenges, we hope to provide a valuable bird’s eye view for both academic and industrial researchers who want to explore the area of PDCs.

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