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Cost-efficient deployment of multi-hop wireless networks over disaster areas using multi-objective meta-heuristics

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ABSTRACT

Nowadays there is a global concern with the growing frequency and magnitude of natural disasters, many of them associated with climate change at a global scale. When tackled during a stringent economic era, the allocation of resources to efficiently deal with such disaster situations (e.g., brigades, vehicles and other support equipment for fire events) undergoes severe budgetary limitations which, in several proven cases, have lead to personal casualties due to a reduced support equipment. As such, the lack of enough communication resources to cover the disaster area at hand may cause a risky radio isolation of the deployed teams and ultimately fatal implications, as occurred in different recent episodes in Spain and USA during the last decade. This issue becomes even more dramatic when understood jointly with the strong budget cuts lately imposed by national authorities. In this context, this article postulates cost-efficient multi-hop communications as a technological solution to provide extended radio coverage to the deployed teams over disaster areas. Specifically, a Harmony Search (HS) based scheme is proposed to determine the optimal number, position and model of a set of wireless relays that must be deployed over a large-scale disaster area. The approach presented in this paper operates under a Pareto-optimal strategy, so a number of different deployments is then produced by balancing between redundant coverage and economical cost of the deployment. This information can assist authorities in their resource provisioning and/or operation duties. The performance of different heuristic operators to enhance the proposed HS algorithm are assessed and discussed by means of extensive simulations over synthetically generated scenarios, as well as over a more realistic, orography-aware setup constructed with LIDAR (Laser Imaging Detection and Ranging) data captured in the city center of Bilbao (Spain).

1. Introduction

In the last few years, different studies based on observed evidences or data-based experiments have shown that the number, frequency and severity of disaster events are sharply increasing around the world [1]. The main rationale for this upsurge of earthquakes, hurricanes, tropical storms, large-area wildfires and other events alike mainly lies in the widely-debated global warming phenomena, which has undoubtedly modified the natural environment of wide geographic areas (e.g., soil dryness, vegetation, orography and other related factors) and increased the risk exposure of the population [2]. Such abrupt changes impact on analytical indicators and climate models, which mostly rely on the relative stationarity of the climate in the short-medium term. Consequently, the effect of global warming on the occurrence of natural disasters has been so far assessed under a several-years-long perspective [3–5].

One of the large-area disasters undergoing a clear increase in its scales, magnitudes and consequences are wildfires. In this context, the report presented at the annual meeting of the American Geophysical Union in San Francisco (USA) in late 2012 predicted that the burned area from wildfires in the USA would double in size by 2050 due to warmer and drier conditions in forthcoming decades [6]. This prediction was buttressed by the record of incidences in that same year, with massive fires affecting Colorado and New Mexico [7]. In addition, when focusing on the spatio-temporal correlation of these events fire events have recurrently happened in nearby locations and close in time due to the propagative essence of the fire when held in isolated areas. A conclusion of utmost importance for the scope of this work is that all the

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above observations lead to the certainty that commanders and decision makers will encounter higher difficulties in the future when allocating resources against disasters due to their simultaneity, colocality and interconnection.

Decisions in this context are driven by well-specified procedures and protocols based on the passive reaction triggered by circumstantial conditions (e.g., a given number of resources for every hectare of terrain affected by the disaster). For instance, several international protocols related to disaster risk reduction have been lately under development by different countries at a worldwide scale, such as the Hyogo Framework for Action (HFA) 2005-2015 [8], the SENDAI Framework for disaster risk reduction 2015-2030 [9,10], the ASEAN Agreement on Disaster Management and Emergency Response (AADMER) [11] and other similar national initiatives. However, cases such as the wildfire happened in a brush-choked canyon north of Phoenix (Arizona, USA) in June 2013 and studies reported in the literature [12,13] showed up the fact that human decision making is subject to errors, partial information and assumptions that may lead to fatalities: in the aforementioned wildfire 19 elite firefighters perished while commanders thought the crew was in a safe place [14]. No extreme had heard each other for 33 min until just before the fire overwhelmed the brigade. In fact there is a plethora of examples where the fatal consequences of team isolation and lack of coordination in wildfires, such as the catastrophic wildfire happened in Guadalajara (Spain) in 2005 [15], or the one occurred in Lüneburg Heath (Lower Saxony, Germany) in 1975 [16]. Certainly decision support tools would have been extremely useful to deploy communication resources in a more effective, active, monitored fashion, discarding any non-supported assumptions from the commanding forces.

When approached from a budgetary perspective, safety should be a reason enough to allocate as much financial resources as available, so as to minimize risk likelihood and consequences severity. Nonetheless, the worldwide economical context of the last few years has restricted stringently national budget items allocated to fire prevention strategies and disaster management methodologies by institutions and governments [17]. For instance, the environmental forum of Castilla La Mancha region (center of Spain) denounces, in their report published in October 2013 [18], that there are only 5 light vehicles in the region with the legally required equipment to combat wildfires (one per province), which incur in delays and an increased risk when performing their duty. Besides, also in that report it is claimed that regional firefighting brigades have undergone significant reductions – reaching up to 50% – in the number of effective hours dedicated to the prevention, surveillance and extinction of wildfires. Even more exemplifying is the fact that the Spanish firefighting campaign for 2013 has dedicated 267 aircrafts for the extinction of wildfires during summertime, 8 units less than in 2012 as a consequence of the funding reductions in the Ministry for Agriculture, Fisheries and Food. Cost, therefore, is called to play an essential role when allocating resources nowadays and in the present future. Current resource allocation procedures, on the contrary, do not take into account any cost criteria in decision making.

Several references from the related literature have addressed this lack of cost effectiveness in the management of resources in disaster situations. For instance, the work in [19] analyzed bidding mechanisms for optimally procuring goods in disaster relief logistics by using an integer programming formulation of the underlying auction operation. The authors in [20] derived a dynamic time-dependent nonlinear model to quantify the influence of a disaster on supply, demand, and humanitarian logistics, and applied Genetic Algorithms to infer the optimal logistic plan minimizing mismatches between the supplied goods and the demand, as well as the time delay of their delivery. Other references in disaster management include the allocation of critical emergency resources in multi-hazard situations [21–23], transport and provisioning under uncertainty [24], supply chain logistics [25] and waste management [26], among many others.

In this context this paper elaborates on a particular yet usual resource allocation problem in disaster management: the deployment of wireless communication relays over a large-scale area wildfire. In practice, the heterogeneity of relay equipment is specially acute in terms of their coverage and cost, ranging from traditional RF front-ends installed on ground vehicles and portable masts to last-generation devices operating from unmanned aerial fleets of drones, helicopters and airplanes. This diversity in the set of deployable relays has led to a large amount of research, gravitating on the similarity of this paradigm with the well-known disk covering problem [27] when exclusively driven by coverage criteria (see e.g., [28–31] and references therein). However, it was not until recently [33] when the authors proposed to include cost aspects in the deployment of relays, as well as in predictive resource provisioning [32]. Following this discussion, this paper builds upon previous work by extending the problem in [33] with the possibility to establish multi-hop links between out-of-coverage brigade units and the relays themselves through other brigades deployed in-between. To efficiently tackle the resulting bi-objective problem, a meta-heuristic solver inspired from music composition is proposed. This manuscript extends early work by the authors in [34] by including the following novel ingredients:

- A thorough survey of the state of the art in what relates to meta-heuristic solvers for communications in disaster scenarios.
- A variant of the problem formulated in [34] aimed at maximizing not only the cost efficiency and coverage of the relay deployment, but also at providing redundancy in the communications of the deployed teams upon eventual cuts in the radio links.
- A modification of the meta-heuristic algorithm aimed at jointly estimating the number of relays to be deployed in addition to their location and model.
- A comparison of the multi-objective performance of the proposed HS-based algorithm with respect to Genetic Algorithms (GA) – which are among the most utilized meta-heuristic solvers in the related literature, as will be later argued – with the same solution encoding scheme.
- Additional simulations over a more realistic problem setup over the city of Bilbao (Bizkaia, Spain) using open LIDAR (Laser Imaging Detection and Ranging) data to estimate realistic line-of-sight coverage areas. As will be shown in the article, the obtained results evince the good performance of the proposed scheme under different values of the admissible number of hops, and pave the way towards its application in real disaster situations.

The rest of the paper is structured as follows: Section 2 surveys the literature related to the technical scope of this article, and Section 3 mathematically formulates the considered problem. Next, Section 4 describes the proposed meta-heuristic solver, whereas Section 5 discusses the obtained simulation results. Finally, Section 6 ends the paper by drawing some concluding remarks.

2. Related work

The growing use of mobile devices during the last decade has allowed for a better and quicker crisis response against disaster events [35]. In such situations, the need for an efficient deployment of wireless communication relays is an extremely challenging real problem to be tackled. It requires interoperability among highly heterogeneous relay equipment in terms of coverage, cost, autonomy and other similar factors, ranging from traditional RF

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