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► **To cite this version:**

Farouk Mezghani, Nathalie Mitton. Opportunistic multi-technology cooperative scheme and UAV relaying for network disaster recovery. *Information*, 2020, 11 (1), 10.3390/info11010037 . hal-02431659

**HAL Id: hal-02431659**

**<https://inria.hal.science/hal-02431659>**

Submitted on 8 Jan 2020

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Article

# Opportunistic multi-technology cooperative scheme and UAV relaying for network disaster recovery

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Version January 6, 2020 submitted to Journal Not Specified

1 **Abstract:** Disaster scenarios have caused crisis situations that have threatened human life.  
2 Particularly, during such events, public communication infrastructure get damaged which impedes  
3 rescue operations and it took a considerable time and effort (days to weeks) before a reliable  
4 communication infrastructure could be restored. Therefore, there is a tremendous need to quickly  
5 deploy communication networks to assist rescue operations for sharing emergency data (e.g. alert  
6 message, rescue instruction). This work evaluates the performances of smartphones and leverages the  
7 ubiquitous presence of mobile devices during disaster scenarios to assist and speed up rescue  
8 operations. It proposes a cooperative communication scheme that exploits available network  
9 technologies and takes various energy levels into account. A multi-tiers network architecture is  
10 proposed targeting a balanced energy consumption in the whole network. Moreover, it introduces  
11 a lifetime efficient data collection scheme that employs drones to scan the disaster area and to visit  
12 mobile devices and relay their data. Extensive simulations have been conducted and results show that  
13 the proposed scheme allows to keep mobile devices alive as long as possible by saving a considerable  
14 energy and guarantees a short drone-path for data relaying.

15 **Keywords:** Disaster recovery, mobile devices, smartphone performances, multi-tier cooperative  
16 communication, drone-based data relaying, performance evaluation, energy-efficient communication  
17

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## 18 1. Introduction

19 Recent major damage from natural disasters (e.g. hurricanes Irma, Maria) have caused crisis  
20 situations that have threatened human life. It took days to weeks before a reliable communication  
21 infrastructure for telephony and Internet services could be restored. Clear situation analyses were  
22 missing, and there was a tremendous need to quickly deploy rescue operations that must be assisted  
23 by communication networks for sharing data to identify and prioritize rescue operations and medical  
24 interventions.

25 In emergency situations where public communication infrastructures fail or are unreliable,  
26 mobile devices (e.g. smartphones, tablets) can be exploited to spontaneously establish a disaster  
27 response communications and opportunistic network to assist rescuers in sharing data. Indeed, some  
28 emergency data issued from survivors (e.g. location data and emergency requests) should be sent  
29 to rescuers but also survivors should receive some fortifying information. Given the light-weight  
30 nature of such messages, leveraging spontaneously mobile devices owned by the survivors is one  
31 possibility. Moreover, opportunistic systems relying on mobile devices can fully leverage their intrinsic  
32 heterogeneous- and ubiquitous-nature. On the other hand, the rescue teams must be able to timely  
33 make use of such information and lead rescue operations efficiently.

34 As mobile devices owned by survivors might be constrained especially in terms of mobility (i.e. it  
35 is difficult to move inside the disaster area), drones have been employed to relay data mainly between  
36 survivors and rescue teams [1–3]. Drones are particularly suitable for such situations as they can  
37 quickly and easily cover affected areas. However, using drones as a communication infrastructure for  
38 disaster recovery raises two key challenges. On the one hand, they should be able to quickly discover  
39 survivors in the disaster area. This requires an energy-efficient communication scheme allowing to  
40 extend the mobile devices lifetime. On the other hand, after discovering all survivors, they should  
41 cover all mobile devices in the considered disaster area in the shortest possible time. This requires a  
42 minimum-time drone path allowing to serve all mobile devices.

43 Offering an alternative way of communication during disaster scenarios has gained increasing  
44 attention in the last few decades [4–7]. However, most of the proposed approaches have considered  
45 mobile devices equipped with a single communication interface (e.g. Cellular or WiFi). Or, nowadays  
46 mobile devices offers multiple network interfaces with different characteristics (e.g. in terms of energy  
47 consumption and transmission range). Relaying data by the aid of UAVs (Unmanned Aerial Vehicles)  
48 has also received increasing attention, mainly in situations where human lives would be endangered  
49 and people cannot be physically reached [1–3]. However, most of recent solutions [8,9] have addressed  
50 the geo-location optimization of drones (i.e. drones height) targeting to maximize its communication  
51 coverage, and they have left behind the communication aspects related to the end devices, mainly, in  
52 terms of energy efficiency.

53 This work addresses these challenges by leveraging mobile devices owned by survivors to assist  
54 search and rescue operations during disaster scenarios. It proposes a cooperative communication  
55 scheme that considers multiple network technologies to opportunistically organize mobile devices  
56 in multiple tiers by targeting a balanced energy consumption in the whole network. Additionally, it  
57 introduces a complementary data relaying scheme that employs UAVs to discover mobile devices, to  
58 visit them and relay data with rescue teams in a minimum path time. The main contributions of this  
59 work are the following.

- 60 – It formally characterizes the creation of a multi-tier communication infrastructure of mobile  
61 devices with multiple radio interfaces. It then derives a heuristic for clustering nodes based on  
62 their local connectivity and available energy.
- 63 – It evaluates the performance of smartphones in terms of network interfaces (based on energy  
64 consumption and transmission range) and clock synchronization.
- 65 – It introduces a scheme for drone-based data collection that minimizes the total flying path, while  
66 still ensuring a sufficient time to collect data. In particular, it derives the locations that a hovering  
67 drone needs to reach and stop at to collect data from mobile devices based on a multi-tier network  
68 structure.

69 Extensive simulations have been conducted and results show that the proposed scheme allows to  
70 keep mobile devices alive as long as possible by saving a considerable energy and guarantees a short  
71 drone-path for data relaying.

## 72 2. Related works

73 Most of the work in wireless sensor networks with mobile elements and ad-hoc networks aim  
74 at providing wireless communication during natural disaster phenomena [7,10–12]. Moreover, the  
75 ubiquitous nature of smart devices such as smartphones is largely exploited by many works, whose  
76 main focus consists of offering an alternative way of communication in areas where communication  
77 infrastructure fail or are unreliable [5,13].

78 Smart devices constitute one key element in survivor-rescuer systems [11,14] – they send out  
79 location data of the survivors to rescue teams, for instance. Accordingly, the works in [1,3] show how  
80 such entities communicate with each other via a complete and autonomous cellular network (i.e. a  
81 small base station carried by drone that fly over a disaster area). However, such works provide no  
82 considerations on the energy-efficiency of the proposed solutions.

Other works with flying ad-hoc networks present performance tradeoffs as a function of parameters such as the UAV height and placement to maximize the coverage in a multi-UAV system [2,15,16]. By contrast, we focus on a single-UAV system which requires no synchronization, placement map over a given area, or task scheduling among UAVs. Moreover, our approach leverages the heterogeneity and ubiquitous nature of smart devices (representing survivors) to build a cooperative scheme underlying the UAV. In fact, such scheme results in a larger number of alive nodes over time, hence ensuring a wider coverage area from which nodes can disseminate their data and ask for help; at the same time, it reduces the flying time (number of stops) of an UAV over the area of interest, hence its energy consumption.

While most of the current work leverages only few of the available network technologies to build their solutions upon [7], the work in [17] exploits all such interfaces for alert diffusion during disasters. However, it only mitigates the energy expenditure of the nodes by scheduling shorter wake-up periods for nodes with low available energy levels. By contrast, this work devises a cooperative and multi-tier communication scheme that achieves energy fairness among the nodes by designating only few nodes to switch on their interfaces and relay the data of the other nodes in the network. Moreover, such nodes vary over time, hence fairly distributing the energy expenditure across all the nodes in the network.

### 3. Multi-technology cooperative communication and drone data relaying

#### 3.1. Multi-technology network architecture

This work proposes COPE, a cooperative communication scheme that leverages mobile devices<sup>1</sup> involving multiple network technologies and characterized by various energy levels such as those available in nowadays mobile devices (e.g., Bluetooth, WiFi, and cellular available in smartphones). These network technologies can be differentiated according to their transmission ranges and energy consumption characteristics [17]. Accordingly, a multi-tiers network architecture, as illustrated in Figure 1, is proposed which consists in opportunistically grouping proximate nodes (i.e. mobile devices that can reach other with a direct communication). Nodes use the same communication technology in each tier and tiers are layered based on their network technology features. In particular, the first (lowest) tier is formed with the lowest energy-consumption communication technology, but also with the shortest transmission range. The highest tier is formed with the highest energy-consumption communication technology, which also offers the highest transmission range. From the lowest to the highest, intermediate tiers are created by increasing transmission ranges and decreasing energy-efficiency levels. The proposed network architecture is flexible to include multiple tiers considering various network technologies. However, for the sake of simplicity, Figure 1 illustrates a network architecture composed of 3 tiers which can correspond to communication technologies available in nowadays mobile devices such as smartphones (e.g. Bluetooth for  $n_1$ -tier, WiFi for  $n_2$ -tier and cellular for  $n_3$ -tier).

In each cluster, one node is elected as cluster-head (CH) which will act as a bridge between different tiers. Indeed, it collects data from nodes belonging to the same clique in its tier and relays them to the upper tier. In the highest tier, CHs communicate directly with the drone which is responsible to relay data between nodes and rescue teams. As an example, as illustrated in Figure 1, node  $s_4$  is the CH for the cluster that includes nodes  $s_5$  and  $s_6$  in the  $n_1$ -tier. Node  $s_2$  is a CH in the  $n_1$  tier for the group that includes nodes  $s_1$  and  $s_3$  and is also a CH in the  $n_2$  tier for the group that contains node  $n_4$ .

The network also involves drones that are sent on-demand to the disaster area as complementary for the data dissemination in addition to the mobile devices. Indeed, drones are considered equipped

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<sup>1</sup> Here, each device (or node) is supposed to be owned by a survivor, therefore, the two terms are used interchangeably in the rest of the article.

127 with the same network technology that forms the highest tier useful to communicate and relay data  
 128 with mobile devices in the upper tier. For instance, they can be carrying an a small cellular base  
 129 station providing an ad-hoc cellular coverage allowing to communicate with to the nodes in the highest  
 130 tier [18,19]. In particular, based on a specific path planning algorithm employed (refer to Section 5  
 131 for more details), a drone visits designated locations in the network, from which it collects data from  
 132 one or more nodes. Going back to the example illustrated in Figure 1, node  $s_2$  is the only one able to  
 133 communicate with the drone in the  $n_3$  tier among all nodes in the clusters it belongs to.

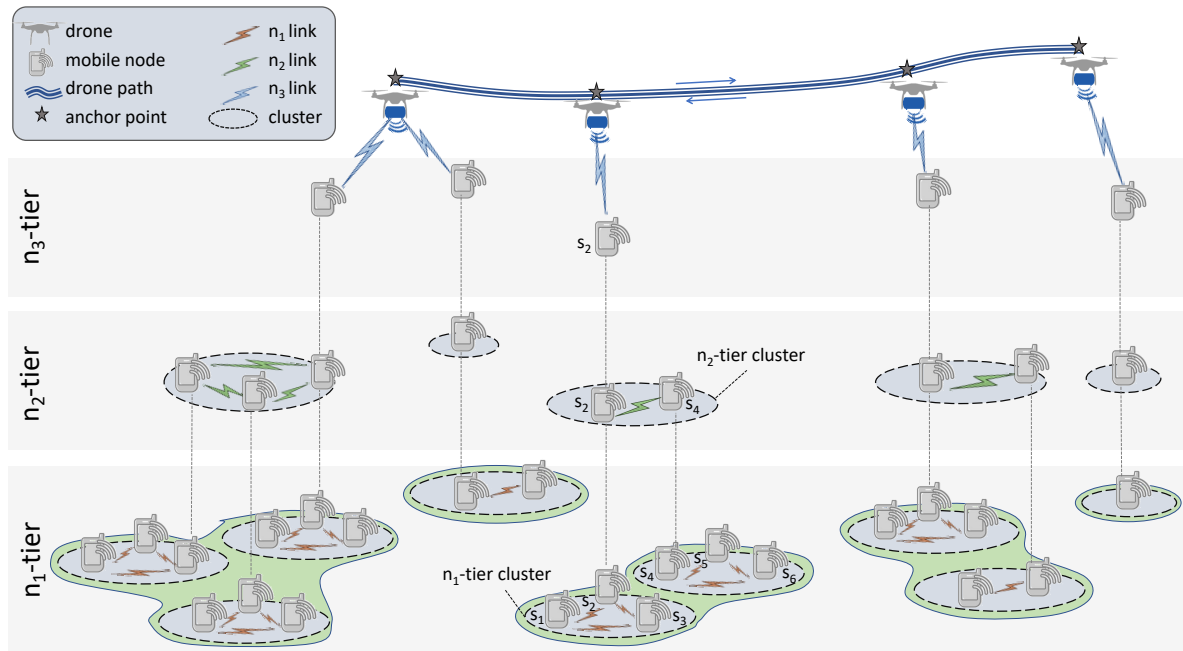


Figure 1. Multi-tier network architecture: (example of three communication technologies)

### 134 3.2. System Model

135 The system includes the set  $\mathcal{S} = \{s_1, s_2, \dots, s_M\}$  of  $M = |\mathcal{S}|$  nodes representing survivors. The  
 136 network density is considered relatively sparse (i.e. nodes might not all be connected). Therefore,  
 137 cluster formation involving multiple nodes is not guaranteed and clusters may be formed with single  
 138 nodes. Each node is characterized by an initial energy (battery) level  $e_{s_m}$ . The system also comprises  
 139 the set  $\mathcal{N} = \{n_u, 1 \leq u \leq U\}$  of communication interfaces, with  $U$  the number of available interfaces.  
 140 Communication interfaces are ordered based on their transmission range  $r$  as  $r_{n_1} < r_{n_2} < \dots < r_{n_U}$  and  
 141 energy consumption  $c$  as  $c_{n_1} < c_{n_2} < \dots < c_{n_U}$ . This assumption will be investigated in next section 4 which  
 142 evaluates the performances of smartphones in terms of energy consumption and transmission range.  
 143 It is considered that mobile devices are carried by survivors who move slowly if at all. Indeed, during  
 144 disasters, survivors might be stacked in one location due to possible injuries or have difficulties to  
 145 move from one location to another due to the obstacles that the natural disaster causes.

146 The system model considers a drone to collect data from nodes and relay them to rescue teams [18,  
 147 20,21]. The drone operates in two phases: it first identifies the location of the nodes in the area affected  
 148 by the disaster and then use them to plan a path and visits all the discovered nodes. The drone flies  
 149 with a constant speed between the different locations at which it stops and hovers for a short period of  
 150 time to exchange data with nodes. More details about drone data relaying are provided in Section 5.

### 151 3.3. Multi-technology communication algorithm

152 A multi-tier communication heuristic is proposed that leverage the opportunistic connectivity of  
 153 nodes at the different tiers to form clusters; CHs can then be designated to uniformly spread energy  
 154 consumption between nodes, both over clusters and tiers. CHs is responsible to transmit data over

**Algorithm 1:** Dynamic CH selection run at each node  $m$ 


---

```

1 Input: nodes location and  $\delta t$  (time-slot)
2 foreach  $\delta t$  do
3    $i = 1$ ;
4   activate interface  $n_1$ ;
5   ACTIVATED = TRUE;
6   while (ACTIVATED==TRUE) and ( $i < U$ ) do
7     discovers  $n_i$ -neighbors and power budget;
8     select  $n_i$  tier CH with higher power-budget (potentially itself);
9     if  $CH_i = m$  then
10      #The node is the CH for  $n_i$ -tier
11      activate  $n_{i+1}$  interface;
12       $i++$ ;
13    else
14      ACTIVATED == FALSE
15  if  $i = U$  then
16    exchange data with UAV

```

---

155 network technologies  $n_u$   $u \leq U$ . Hence, mobile devices of CHs consume energy faster than other  
156 nodes. To maximize the lifetime of clusters, nodes belonging to the same cluster take turns becoming  
157 CH for a time period  $\delta t$  according to their battery level (i.e. the node having the highest energy level  
158 will be designated as CH). The heuristic is described in Algorithm 1.

#### 159 4. Mobile devices performances: Smartphone use case

160 We have carried out experiments to evaluate smartphones network interfaces performances  
161 (based on their energy consumption and transmission range) and clock synchronization. Experimental  
162 results can be useful to support technological choices for rescue operations.

163 Testing experiments have been conducted featuring six smartphones (model: Wiko Tommy 2)  
164 involving two communication interfaces Bluetooth and WiFi. Table 1 shows the main smartphones  
165 characteristics. We have deployed the COPE communication solution (android application) on  
166 the different smartphones and testing scenarios have been conducted to evaluate smartphones  
167 performances in terms of energy consumption, transmission range and clock synchronization based  
168 on the proposed cooperative communication scheme COPE.

**Table 1.** Smartphones characteristics

Model	Wiko Tommy 2
OS	Android 7.1 (Nougat)
Battery	Li-Po 2500 mAh 9.5 Wh
Bluetooth	4.1, A2DP, Low Eenergy
WiFi	WiFi Direct

##### 169 4.1. Energy consumption & Transmission range

170 COPE proposes a multi-technology cooperative communication for a fair energy consumption  
171 in the whole network. Experiments were conducted to measure the energy consumption based on a  
172 non-cooperative and cooperative network topologies as follows:

- 173 (i) a non-cooperative communication scheme considering only one node that operates individually;  
174 i.e. nodes switch on their network interfaces (Bluetooth and WiFi direct) for communication
- 175 (ii) a cooperative communication scheme (i.e. COPE) considering two and three nodes respectively;  
176 i.e. nodes form groups based on the Bluetooth, then, periodically only one node turn on its WiFi  
177 interface at the same time to communicate

178 For measurements, only COPE application was running on smartphones with the screen turned off.

179 Figure 2 shows the energy consumption of the network interfaces Bluetooth and WiFi during 5 min.  
180 The figure shows that the non-cooperative approach (i.e. nodes operate individually) consumes more  
181 energy than cooperative-based approach. Moreover, energy consumption reduces by increasing the  
182 number of nodes cooperating within the same group. Indeed, for a bigger group, nodes will be turning  
183 off their WiFi interface for longer time. Therefore, a multi-technology cooperative communication  
184 scheme as COPE allows to reduce the energy consumption which can help to maintain mobile devices  
185 alive as long as possible.

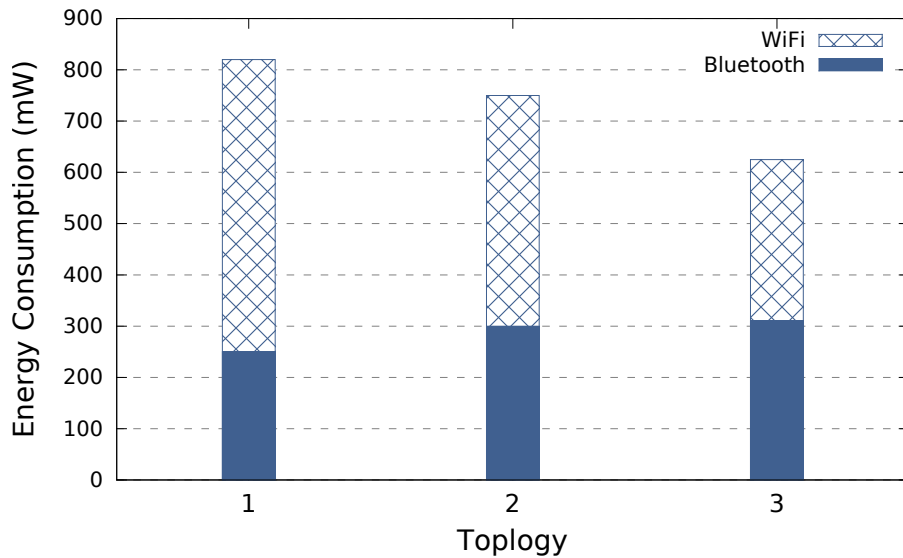


Figure 2. Energy consumption

186 Experiments have been conducted to measure the transmission range of both WiFi-Direct and  
187 Bluetooth. Evaluating the link quality and transmission speed is not in the scope of this work (see  
188 [22] for a related study). Indeed, during disasters, we believe the importance of exchanging short text  
189 messages useful to alert and to ask for assistance. Therefore, we have considered testing scenarios  
190 based on exchanging messages of only a few bytes in length. We have considered different testing  
191 conditions; i.e. weathers (calm and dry/humid and windy); indoor communication with obstacles (1 to  
192 2 walls); outdoor communication with a good line of sight (see yellow lines on Figure 3); inter-buildings  
193 communication (see red line on Figure 3).





Figure 3. Transmission range testing area

194 Table 2 shows the transmission range of both Bluetooth and Wi-Fi Direct for indoor and outdoor  
 195 scenarios. Results show that the Bluetooth version 4.1 offers an important coverage compared to  
 196 previous Bluetooth versions. Most of research works consider a 10 m transmission coverage for the  
 197 Bluetooth which has to be re-evaluated considering the improvement made on the Bluetooth Low  
 198 Energy (BLE).

Table 2. Bluetooth and Wi-Fi Direct transmission range

	Bluetooth	Wi-Fi Direct
Indoor	35 m	$\geq 100$ m
Outdoor	50 m	$\geq 100$ m

199 These experiments confirms our assumptions in COPE scheme by ranking network interfaces  
 200 based on their energy consumption and transmission range considering applications requiring an  
 201 exchange short messages. We have considered that WiFi offers a higher transmission range and  
 202 consumes more energy than Bluetooth.

#### 203 4.2. Clock Drift

204 The proposed cooperative communication scheme, COPE, considers that mobile devices are  
 205 already synchronized with millisecond accuracy before disasters occurs. Indeed, smartphones  
 206 periodically synchronize their time (each day) from telecom operators. We investigate the clock  
 207 drift between smartphones to check the necessity of an additional clock synchronization during the  
 208 post-disaster period.

209 Testing experiment has been conducted to measure the clock drift of the 6 smartphones. All  
 210 smartphones were initially synchronized via an NTP (Network Time Protocol) time server and we  
 211 measured the clock drift.

212 Figure 4 illustrates the clock drift of the 6 smartphones during 24 hours and it shows that  
 213 smartphones desynchronize by up to 0.3 s during 24 hours. Such desynchronization has no impact on  
 214 COPE and thus no additional synchronization is required. We have obtained similar results measuring



215 the clock drift considering other conditions: running various applications on smartphones, charging  
 216 smartphones and turning on the smartphones display.

217 We have noticed that smartphones present different clock drift behaviors even though the same  
 218 smartphone model has been used.

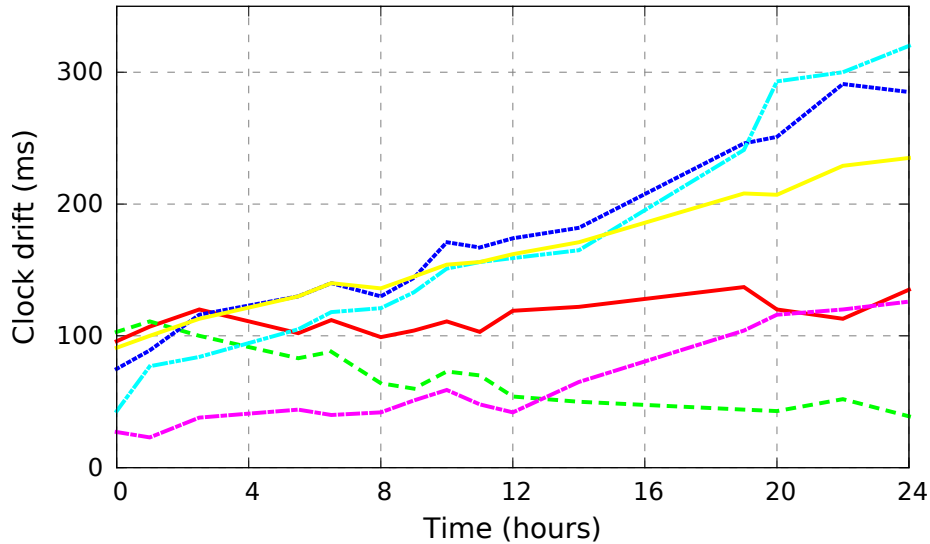


Figure 4. Smartphones clock drift

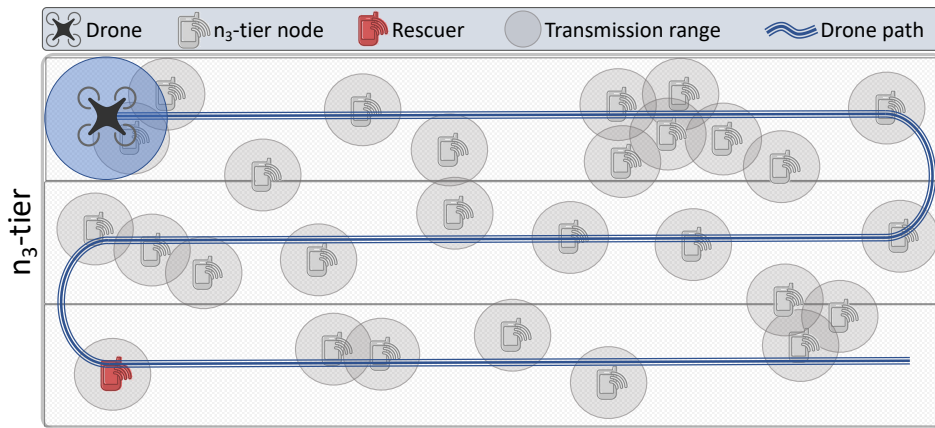
## 219 5. UAV Data Relaying

220 During a disaster, using an additional way of communication to relay data between rescue teams  
 221 and different zones in the disaster area would ease and speed up the rescue operations. Thus, UAVs  
 222 have gained increasing attention as they can move easily from one place to another and they can  
 223 communicate and relay data with other devices. However, UAVs are characterized by their high  
 224 cost and limited battery lifetime. Therefore, it is of great importance to efficiently use UAVs such to  
 225 optimize their paths when relaying data.

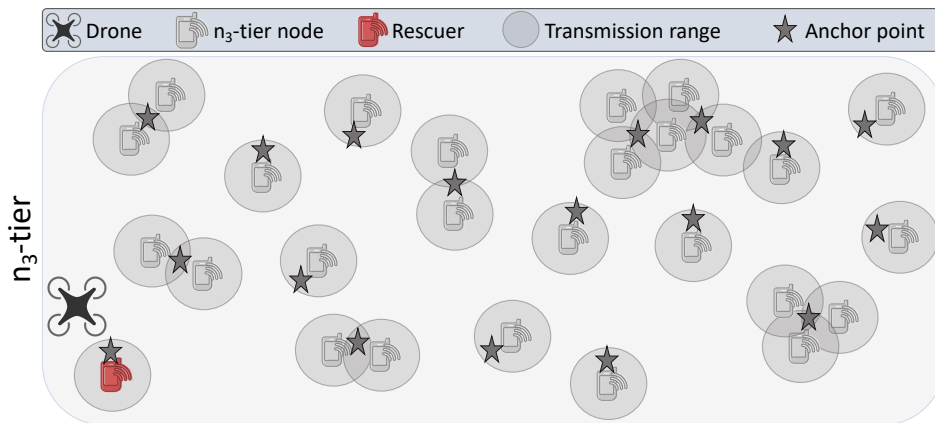
226 We assume the SOS and all data sent by survivors' nodes relayed to the upmost tiers nodes can  
 227 be collected and reported to rescue teams through the use of drones equipped with the upmost tiers  
 228 communication technology, e.g. femto-cells as an on-demand communication infrastructure [8,16]. In  
 229 order to collect all data and enable efficient communication to and from the nodes, the drone must  
 230 visit all the upmost tier nodes (i.e., nodes in the  $n_U$  tier). Our solution operates in two phases.

- 231 • *Search.* A drone flies over the area affected by the disaster so as to discover nodes and store their  
 232 location. The drone follows an S-shaped route, whose curvature guarantees that all nodes can be  
 233 discovered (see Figure 5).
- 234 • *Anchor points derivation and path planning.* Once the nodes are discovered, one can derive anchor  
 235 points. We define an anchor point as a location at which the drone should hover to collect data.  
 236 It can be either directly or  $n_U$  tier node or, when possible, a locations from which it is in range of  
 237 several  $n_U$  tier nodes (Figure 6) such that hovering above the (fewer) anchor points suffices to  
 238 serve all  $n_U$  tier nodes. Then, a path planning algorithm is run to compute the shortest path that  
 239 visits all these anchor points. The drone then follows such a path and collects data (Figure 7).

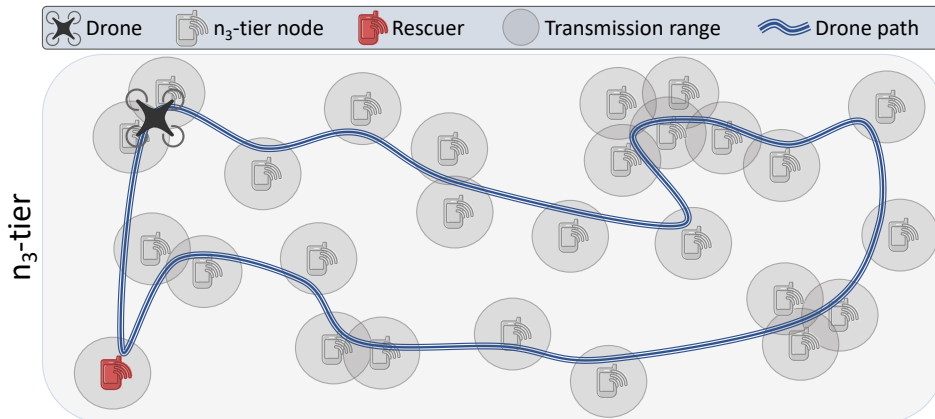
240 Different schemes to plan the drone's path that dictate the order of visit of the points are considered.  
 241 They mostly aim to find the shortest path that goes through all such points considering that the drone  
 242 eventually returns to its initial location (to recharge, for instance). Such a problem, in fact, corresponds  
 243 to the well-known NP-hard TSP problem. Other versions such as TSPN (TSP with Neighborhoods),  
 244 CETSP (Close-Enough TSP), Covering Tour Problem, and Generalized TSP are extensively studied in  
 245 literature [23,24].



**Figure 5.** During the search phase a drone flies over the area affected by a disaster and stores the location of the discovered nodes in the highest (i.e.,  $n_3$ ) tier of the network.



**Figure 6.** Drone anchor points shown with stars



**Figure 7.** Shortest path for a drone to visit all the anchor points

246 Generally, the path is planned to reduce the drone's energy consumption of the drone. These  
 247 algorithms aim to shorten the tour length, and yet the the time of a tour to collect the data from the  
 248 nodes over a disaster area. More specifically, leveraging the cooperative communication and data  
 249 relay protocol among the nodes underlying the UAV yields to reducing the number of points a drone  
 250 should visit. In fact, identifying anchor points from which a drone can serve more than one node  
 251 results in a lower number of stops for the drone. Feeding such anchor points  $i$  to the existing TSP and

**Table 3.** Summary of used parameters.

Parameter	Value
Disaster area	10 km x 5 km
Drone speed	10 m/s
Minimum hovering time	5 s
Drone- $n_3$ tier node data exchange time	2 s
Bluetooth tx range / power consumption	100 m / 50 mW
WiFi tx range / power consumption	200 m / 70 mW
Cell tx range / power consumption	500 m / 120 mW

252 CETSP algorithms [23,24] comes down to construct the shortest path for a drone to follow, as shown in  
 253 Figure 7.

## 254 6. Performance Evaluation

255 We evaluate our model regarding two main aspects: (i) the energy gain from the survivors'  
 256 perspective when they cooperate and build our multi-tiers architecture, and (ii) the energy gain from  
 257 the UAV perspective when hovering over our multi-tiers architecture. Specifically, experimental results  
 258 are obtained through trace-driven simulations in a realistic disaster scenario. We report the average  
 259 values over several simulation runs along with the related standard deviation when meaningful.

### 260 6.1. Cooperative Multi-tier Data Relaying

#### 261 6.1.1. Methodology and Setup

262 We assess the performance of our multi-tier data relay architecture (Algorithm 1) and compare it  
 263 to the ones of baseline and static schemes.

- 264 • *Baseline approach.* It considers no cooperation between nodes that act independently of each  
 265 others. Every node is assumed to activate all its network interfaces to transmit its own data.  
 266 In fact, all nodes are exposed to a maximum energy expenditure, which leads to fast battery  
 267 depletion. Consequently, the chances of a node to keep in contact with search and rescue teams  
 268 for long periods of time are subject to such a limitation.
- 269 • *Static approach.* Similarly to COPE, the static approach allow the nodes to collaborate and  
 270 self-organize into clusters at the lowest tier. A CH is selected per cluster to activate its upper tier  
 271 communication interface and again select a representative, as in COPE. Consequently, the other  
 272 cluster members do not need to switch on the next communication interface, hence mitigating  
 273 their energy consumption. The CHs of each tier are selected based on the initial information on  
 274 their energy budget of the nodes (the node with the highest available energy level in the cluster  
 275 becomes the head). The status of such a node remains invariant over time until its energy fully  
 276 depletes, which leads to selecting a new CH. Although the static approach provides collaboration  
 277 among the nodes, it puts the energy expenditure burden on the *static* CHs only.

278 We consider a disaster scenario with of a varying number of survivors randomly distributed over  
 279 an urban area of 5 by 10 kilometers. We assume each survivor is equipped with a mobile device (e.g.  
 280 smartphone) equipped with three traditional network interfaces: Bluetooth, WiFi and cellular, with  
 281 transmission range of 100 m, 200 m, and 500 m correspondingly. We assume Bluetooth, WiFi and  
 282 cellular energy consumption is respectively 50 mW, 70 mW and 120 mW as shown in [25,26]. Moreover,  
 283 each node is assigned a random initial energy level in the range of [10 kJ,20 kJ]. Such parameters are  
 284 summarized in Table 3.

### 285 6.1.2. Obtained Results.

286 We consider a node dies when it has no energy left. Figure 8 shows the number of alive nodes  
 287 when 400 nodes are randomly distributed follow three different communication schemes (baseline,  
 288 static, and the dynamic COPE one). It shows that the baseline scheme performs poorly in terms of  
 289 network lifetime and consumption fairness. Indeed, nodes quickly die and the network does not  
 290 survive beyond the golden relief time. The dying trend is almost linear, which is as expected since each  
 291 node is accountable only for itself, whatever the existence or not of other nodes. As a result, most of  
 292 nodes deplete their battery at the same time instant. Thanks to the node cooperation they introduced,  
 293 the other schemes lead to a higher number of alive nodes for each time instant. The static scheme leads  
 294 to at least 50 alive nodes more than the baseline scheme and this gap increases over time. Furthermore,  
 295 the "dying" trend is smoothed. The static scheme and the nodes' opportunistic organization almost  
 296 double the network lifetime (or the time at which all nodes are dead). Our proposed dynamic scheme  
 297 outperforms both other schemes thanks to its energy expenditure fairness mechanism. It increases the  
 298 number of alive nodes at a given time instant compared to the other two schemes. Moreover, most of  
 299 the nodes die alone, or in smaller groups and tends to balance energy over nodes. Therefore, it results  
 300 in the last alive nodes dying together or dying within a short period of time. This also explains the fact  
 301 that the static scheme slightly outperforms the dynamic one in the last two hours, approximately from  
 302 hour 6 to 8.

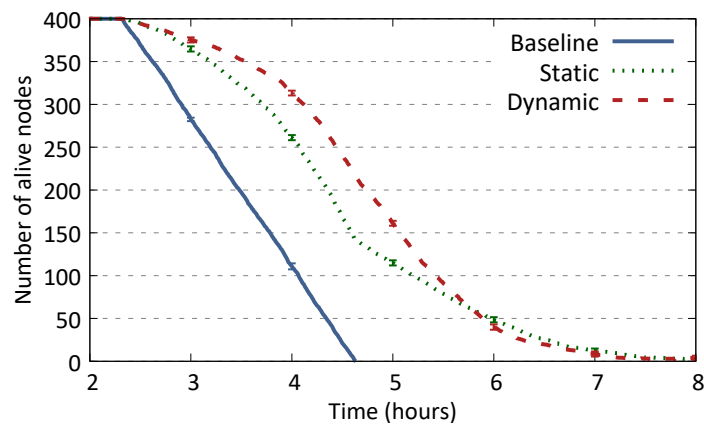
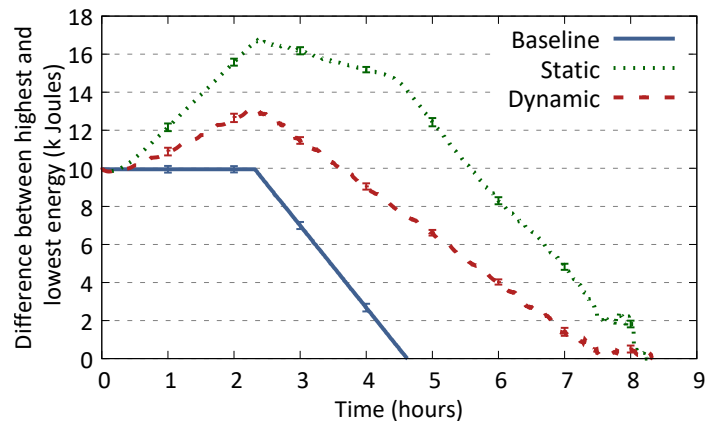


Figure 8. Number of alive nodes over time

303 Figure 9 depicts the difference between the highest and lowest energy level of nodes over time.  
 304 As previously in Figure 8, the strategies that enable cooperation between nodes (static and dynamic)  
 305 obtain the best results, the minimum difference between the energy levels. The initial rise of the  
 306 difference between the energy levels could be explained by the fact that the nodes with initial low  
 307 available energy levels deplete their batteries soon after the data dissemination starts. However, in the  
 308 dynamic case, the remaining nodes consume equally their energy, smoothing the difference between  
 309 the highest and lowest levels. In the static case, few nodes consume energy for all (the CHs), therefore  
 310 the energy gap between the nodes increases. Moreover, the difference between the energy levels  
 311 in the baseline case presents a steep slope because all the nodes in the network are responsible to  
 312 communicate directly with a drone, hence they switch on all the network interfaces at the same time.  
 313 Though the energy burden is equally distributed, the energy of the nodes depletes almost twice as fast  
 314 as the cooperative-based schemes.



**Figure 9.** Difference between the highest and the lowest energy values in the network

## 315 6.2. Cooperative Data Relaying with UAVs

### 316 6.2.1. Methodology and Setup.

317 We evaluate the performance of the proposed TSP and CETSP algorithms considering cooperation,  
 318 namely the TSP-COPE and CETSP-COPE and compare it to the performance of TSP and CETSP where  
 319 no cooperation is considered among nodes (i.e. selfish approach where nodes operates individually).  
 320 In the following, we compare between the four path planning algorithms:

- 321 • TSP: computes the shortest path that visits each node in the network (no multi-tier cooperation  
 322 is considered among nodes).
- 323 • CETSP: finds the minimum number of stops (i.e. anchor points) from which the drone can  
 324 communicate with all nodes without having to stop at each of them. Then, it computes the  
 325 shortest path that visits all the stops.
- 326 • TSP-COPE: similar to TSP, where node cooperation is supported; the shortest path is computed  
 327 based on the highest tier nodes.
- 328 • CETSP-COPE: similar to CETSP, where node cooperation is supported; the shortest path is  
 329 computed based on the anchor points obtained from the highest tier nodes.

330 The following assesses and compares the performance of the two proposed TSP-COPE and  
 331 CETSP-COPE algorithms (see Section 5) with the selfish TSP and CETSP algorithms. All the four  
 332 schemes have been implemented as additional modules to the ONE simulator<sup>2</sup>. The considered  
 333 scenarios consist of various network densities, where the nodes are randomly situated in an urban  
 334 area. A drone flies over the disaster area with a speed of 10 m/s. We assume that 2 s is a sufficient time  
 335 to exchange data with a node, especially given the fact that the data, generally in disaster scenarios,  
 336 consists of light-weight messages useful for rescue operations and assistance. However, we consider a  
 337 *time-guard* of a minimum of 5 s for a drone to hover above a node. Moreover, the hovering time of a  
 338 drone extends in proportion to the cardinality of the cluster that the node is CH of. For instance, a  
 339 drone visiting a CH point of a cluster of three members would stop for a time of max (5 s, 6 s). We  
 340 impose such time-guards to take into account for possible unsuccessful transmissions or collisions.

### 341 6.2.2. Obtained Results.

342 Figures 10, 11, 12 show the number of stops, the length, and time of a drone tour in terms of the  
 343 number of nodes in the network. Figure 10 shows how the number of stops of a drone reduces for

<sup>2</sup> <https://akeranen.github.io/the-one/>



344 the two proposed schemes that consider cooperation among nodes, i.e. TSP-COPE and CETSP-COPE.  
 345 In fact, while the number of stops of the TSP scheme with no cooperation increases linearly with the  
 346 network density, the CETSP-COPE instead shows how the number of stops increases slowly with the  
 347 network density. Moreover, there is a clear trend, i.e., almost a stable number of stops, for networks  
 348 with high density. Indeed, as the network density increases, the multi-tier cooperation among nodes  
 349 becomes more efficient as nodes have more neighbors, hence more and bigger clusters are formed. In  
 350 fact, the number of stops reduces by more than 70% for a density of 500 nodes. Figures 11 and 12 show  
 351 how our proposed CETSP-COPE scheme outperforms the schemes with no cooperation among the  
 352 nodes to relay data. This is clearly shown by the fact that the tour length is reduced by more than  
 353 half, and that the drone flying and hovering time reduces by  $\approx 60\%$  for a high network density. In  
 354 details, Figure 11 shows that the difference in the tour length for the four schemes increases with the  
 355 node density; the CETSP-COPE tour length is, in fact, half that of the TSP one. Similarly, the flying  
 356 and hovering time of a drone shown in Figure 12, increases very slowly for the schemes that support  
 357 cooperation, while such values are at least 30% higher for the TSP scheme and high node densities in  
 358 the network. For instance, the CETSP-COPE drone tour time reduces by around 50% compared to the  
 359 TSP for 500 nodes in the network. However, CETSP outperforms TSP-COPE and that can be explained  
 360 by the fact that the cellular transmission range results in a drone to dictate fewer anchor points to visit  
 361 than the number of  $n_3$  tier CHs designated based on node cooperation, hence TSP-COPE.

362 The energy expenditure of a drone depends mostly on the hovering time [27]. Our cooperative  
 363 schemes, i.e. TSP-COPE and CETSP-COPE, offer low hovering times compared to flying ones, even for  
 364 high network density. Such a trend, presented in Figure 12, shows that the hovering time (proportional  
 365 to the number of stops) keeps at low levels for all network densities. That is because more clusters  
 366 with big cardinality are formed as the network density increases, hence a limited number of  $n_3$  tier  
 367 nodes relay the data of all the underlying tier nodes. Moreover, even the flying (movement) time,  
 368 which constitutes most of a drone tour time, is further reduced by our cooperative schemes.

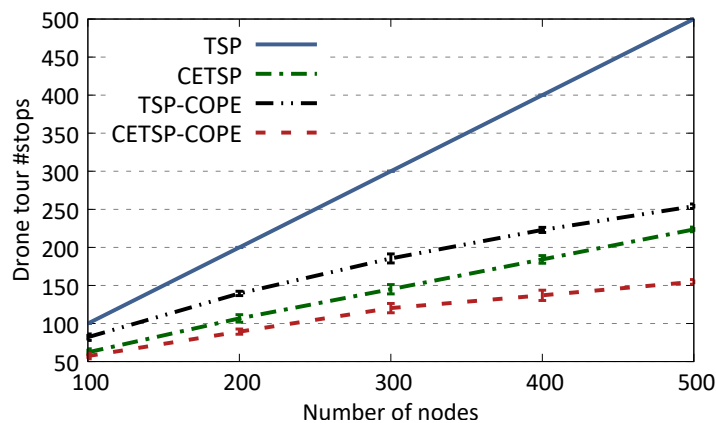


Figure 10. Number of stops

## 369 7. Open challenges and Future Directions

370 In this section, we browse a non exhaustive list of some open challenges and potential research  
 371 directions to investigate to complete and/or improve our architecture efficiency.

### 372 7.1. Survivor and rescuer mobility

373 We have assumed that survivors have a low mobility since they could be wounded and buried  
 374 under rubble. Our scheme periodically re-computes cliques and time to serve as a representative at  
 375 each communication layer and thus is assumed to be reliable to faster mobility schemes but this should  
 376 be better investigated. In addition, as in our approach, all nodes are not all active at the same time,

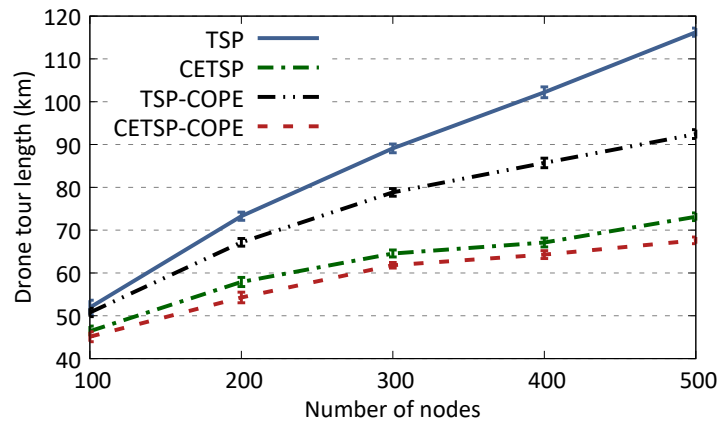


Figure 11. Tour length

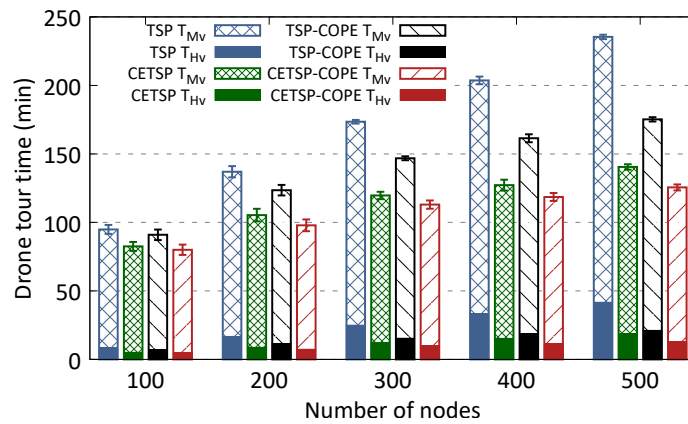


Figure 12. Drone hovering and flying time

377 rescuers or drones can be in range of a survivor at a given time but not of its representative during this  
 378 period and thus messages can be missed.

### 379 7.2. Belonging to multiple cliques

380 Depending on their connectivity, devices could also be associated with multiple cliques as depicted  
 381 by Figure 13 with the node  $S_2$ . However, such an option is out of the scope of this article. Indeed, we  
 382 simply assume that such nodes will choose to belong only to the smallest clique for balance purpose.  
 383 Smarter schemes that dynamically adapt the clique membership could be investigated.

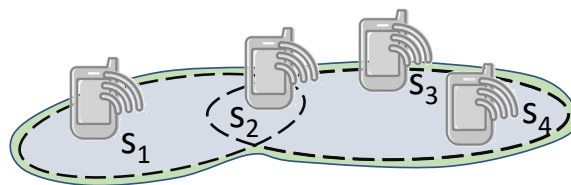


Figure 13. Example of clique multi-membership

### 384 7.3. Devices heterogeneity

385 Our approach is robust to a set of devices featuring different amount of remaining energy. We  
 386 experimentally verified our assumptions on the possibility to rank communication technologies  
 387 based on their ranges and costs [28] for a homogeneous set of devices. Nevertheless, as it has been  
 388 highlighted by a recent study [22], the signal reception quality of a given signal greatly depends of the

389 hardware used and of different settings. Yet, our assumption may not be verified in all cases. But, as  
390 it only uses connectivity information between devices to form cliques and so is robust to imperfect  
391 propagation ranges and unilateral links. Not verifying this assumption would result in non-optimal  
392 energy consumption. So, more investigation should be performed to quantify the impact of this  
393 heterogeneity in devices and propagation ranges. In addition, our goal is to rely opportunistically on  
394 all available devices that could support the data collection at the rescue center. Therefore, it could  
395 include other pieces of infrastructures such as base stations that are still active and powered but  
396 disconnected to the core network. They could still act as strong relays since benefiting from an infinite  
397 energy reserve. In our scheme, such strong access points will naturally be representative of a clique for  
398 all other nodes but our scheme does not leverage its potential longer range and more likely connectivity  
399 with several cliques.

#### 400 *7.4. Unavailability of some communication interfaces*

401 In our approach, we have assumed that all devices are equipped with all same communication  
402 interfaces but for different reasons, this could not be the case. Some interface may be unavailable  
403 because the device has not been equipped with it, or it is damaged or the environment does not  
404 affect all interfaces similarly. This is thus worth integrating in our scheme the fact that all devices can  
405 represent the clique for a given layer.

#### 406 *7.5. Multi-drones*

407 Our scheme currently investigates the use of a single drone and could be simply extended to the  
408 use of several drones by sharing between them the areas or anchor nodes to cover. However, due to  
409 the dynamics of the anchors at the upmost layers, such a static splitting might not be optimal and a  
410 dynamic area responsibility could be set as in [29].

#### 411 *7.6. Dynamic 3D drones path planning*

412 Currently, we assume that thanks to the upmost layer nodes discovery and location, drones are  
413 able to compute anchor points and the best traveling path visiting all these anchor points. We also  
414 assume that at each visit, nodes inform the drone about change in upmost layer representative allowing  
415 it to recompute its path. The path computing is realized in 2 steps: first compute the anchor points  
416 and then draw a (Close Enough) traveling salesman problem trajectory. This does not consider the  
417 drone autonomy nor a drastic change in representative positions and computes a 2D path. But drone  
418 coverage depends on the drone altitude and speed; the drone presents a highly flexible 3-D mobility  
419 and the higher the altitude, the larger the coverage but the higher the energy consumption [30]. And  
420 this could change the anchor points determination since by flying at a higher altitude, the drone will  
421 cover more nodes at a time but will consume more energy. An open problem is thus to determine  
422 the best energy-efficient and minimum-time 3D path to travel the area as fast as possible while still  
423 remaining in range of each survivor long enough to assure full servicing. This path should jointly  
424 investigate the drone trajectory and the location of the anchor nodes that could dynamically be adapted  
425 with drone altitude, while still integrating the pitstop duration at each anchor point, which has a  
426 mandatory minimum duration and should be proportional to the number of nodes to serve at this  
427 position [31].

## 428 **8. Conclusions**

429 This work investigates drone-assisted communications for disaster recovery scenarios. It proposes  
430 a dynamic scheme of communication that opportunistically leverages multiple network technologies  
431 integrated in to mobile devices, while leveraging the heterogeneity of such devices in terms of available  
432 energy levels. Extensive simulations have been conducted and results have shown the benefits of the  
433 proposed scheme from both, the drone and the survivors perspective. On the one hand, the proposed  
434 scheme allows to maintain a longer and maximum network coverage considering a cooperative scheme

435 which enables, with the support of high-energy nodes, low-energy nodes to preserve their battery for  
436 longer time. On the other hand, our proposed solution reduces the energy consumption of the drone  
437 by minimizing the number of nodes it visits (i.e. anchor points) and therefore, it reduces the drone  
438 path length. However, the advantages of such a solution can be further exploited by introducing a  
439 further control parameter – the drone height. Indeed, extending the evaluation presented here to take  
440 account of such a parameter is a promising future work.

441 **Author Contributions:** Farouk Mezghani and Nathalie Mitton were responsible for the main idea. They  
442 conceived and designed the algorithm, and wrote the manuscript; Farouk Mezghani carried out the simulations  
443 and run the experiments.

444 **Funding:** This work was partly supported by CPER DATA and the Hauts de France PIPA project.

## 445 References

- 446 1. Gupta, L.; others. Survey of important issues in UAV communication networks. *IEEE Comm. Surveys & Tutorials* **2016**.
- 447 2. Mozaffari, M.; Saad, W.; Bennis, M.; Debbah, M. Unmanned aerial vehicle with underlaid device-to-device  
448 communications: Performance and tradeoffs. *IEEE Transactions on Wireless Communications* **2016**.
- 449 3. Zeng, Y.; Zhang, R.; Lim, T.J. Wireless communications with unmanned aerial vehicles: opportunities and  
450 challenges. *IEEE Com. Mag.* **2016**.
- 451 4. Martín-Campillo, A.; others. Evaluating opportunistic networks in disaster scenarios. *J. of Network and  
452 computer applications* **2013**.
- 453 5. Quispe, L.E.; Galan, L.M. Behavior of Ad Hoc routing protocols, analyzed for emergency and rescue  
454 scenarios, on a real urban area. *Expert systems with applications* **2014**.
- 455 6. Yuan, P.; others. Recent progress in routing protocols of mobile opportunistic networks: A clear taxonomy,  
456 analysis and evaluation. *JNCA* **2016**.
- 457 7. Lu, Z.; Cao, G.; La Porta, T. TeamPhone: Networking Smartphones for Disaster Recovery. *IEEE Trans. on  
458 Mobile Computing* **2017**, 16.
- 459 8. Lyu, J.; Zeng, Y.; Zhang, R.; Lim, T.J. Placement optimization of UAV-mounted mobile base stations. *IEEE  
460 Communications Letters* **2017**, 21, 604–607.
- 461 9. Lyu, J.; Zeng, Y.; Zhang, R. Cyclical multiple access in UAV-aided communications: A throughput-delay  
462 tradeoff. *IEEE Wireless Comm. Letters* **2016**, 5, 600–603.
- 463 10. Wex, F.; Schryen, G.; Feuerriegel, S.; Neumann, D. Emergency response in natural disaster management:  
464 Allocation and scheduling of rescue units. *European Journal of Operational Research* **2014**.
- 465 11. Ochoa, S.F.; Santos, R. Human-centric wireless sensor networks to improve information availability during  
466 urban search and rescue activities. *Information Fusion* **2015**, 22, 71–84.
- 467 12. Chakchouk, N. A survey on opportunistic routing in wireless communication networks. *IEEE  
468 Communications Surveys & Tutorials* **2015**.
- 469 13. Nishiyama, H.; others. Relay-by-smartphone: realizing multihop device-to-device communications. *IEEE  
470 Comm. Mag.* **2014**.
- 471 14. Ramchurn, S.D.; Wu, F.; Jiang, W.; Fischer, J.E.; Reece, S.; Roberts, S.; Rodden, T.; Greenhalgh, C.; Jennings,  
472 N.R. Human-agent collaboration for disaster response. *Autonomous Agents and Multi-Agent Systems* **2016**.
- 473 15. Bekmezci, I.; Sahingoz, O.K.; Temel, Ş. Flying ad-hoc networks (FANETs): A survey. *Ad Hoc Networks* **2013**.
- 474 16. Mozaffari, M.; Saad, W.; Bennis, M.; Debbah, M. Efficient deployment of multiple unmanned aerial vehicles  
475 for optimal wireless coverage. *IEEE Communications Letters* **2016**.
- 476 17. Mezghani, F.; Mitton, N. Alternative opportunistic alert diffusion to support infrastructure failure during  
477 disasters. *Sensors* **2017**.
- 478 18. Namuduri, K. When Disaster Strikes, Flying Cell Towers Could Aid Search and Rescue. *IEEE SPECTRUM*  
479 **2017**.
- 480 19. Singh, R.; Thompson, M.; Mathews, S.A.; Agbogidi, O.; Bhadane, K.; Namuduri, K. Aerial Base Stations  
481 for Enabling Cellular Communications during Emergency Situation. *ICVISP*, 2017.
- 482 20. Merwaday, A.; Guvenc, I. UAV assisted heterogeneous networks for public safety communications.  
483 *Wireless Communications and Networking Conference Workshops (WCNCW)*, 2015 IEEE, 2015.
- 484

- 485 21. Mozaffari, M.; Saad, W.; Bennis, M.; Debbah, M. Drone small cells in the clouds: Design, deployment and  
486 performance analysis. *Global Communications Conference (GLOBECOM)*, 2015.
- 487 22. Bertier, C.; Dias De Amorim, M.; Benbadis, F.; Conan, V. Modeling Realistic Bit Rates of D2D  
488 Communications between Android Devices. *ACM International Conference on Modeling, Analysis  
489 and Simulation of Wireless and Mobile Systems (MSWiM)*; , 2019.
- 490 23. Gulczynski, D.J.; Heath, J.W.; Price, C.C. The close enough traveling salesman problem: A discussion of  
491 several heuristics. *Perspectives in Operations Research* **2006**, pp. 271–283.
- 492 24. Gendreau, M.; Laporte, G.; Semet, F. The covering tour problem. *Operations Research* **1997**.
- 493 25. Putra, G.D.; others. Comparison of energy consumption in Wi-Fi and bluetooth communication in a Smart  
494 Building. *Computing and Communication Workshop and Conference (CCWC)*, 2017.
- 495 26. Perrucci, G.P.; Fitzek, F.H.; Widmer, J. Survey on energy consumption entities on the smartphone platform.  
496 The 73<sup>rd</sup> Vehicular Technology Conference (VTC Spring), 2011.
- 497 27. Di Franco, C.; Buttazzo, G. Energy-aware coverage path planning of UAVs. *ICARSC*, 2015.
- 498 28. Mezghani, F.; Mitton, N. Benchmarking smartphone performances for cooperative disaster alert diffusion.  
499 *Adhoc Now*, 2018.
- 500 29. Razafindralambo, T.; Mitton, N.; Carneiro Viana, A.; Dias De Amorim, M.; Obraczka, K. Adaptive  
501 Deployment for Pervasive Data Gathering in Connectivity-Challenged Environments. *Eighth Annual IEEE  
502 International Conference on Pervasive Computing and Communications (PERCOM)*; IEEE: Mannheim,  
503 Germany, 2010; pp. 51–59.
- 504 30. Zorbas, D.; Pugliese, L.D.P.; Razafindralambo, T.; Guerriero, F. Optimal drone placement and cost-efficient  
505 target coverage. *Journal of Network and Computer Applications* **2016**.
- 506 31. Mezghani, F.; Mitton, N. Open problem: Energy-and time-efficient dynamic drone path planning for  
507 post-disaster network servicing. *ODS 2018 - International Conference on Optimization and Decision  
508 Science*; , 2018.

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