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Article

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

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

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

1. Introduction

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

In emergency situations where public communication infrastructures fail or are unreliable, mobile devices (e.g. smartphones, tablets) can be exploited to spontaneously establish a disaster response communications and opportunistic network to assist rescuers in sharing data. Indeed, some emergency data issued from survivors (e.g. location data and emergency requests) should be sent to rescuers but also survivors should receive some fortifying information. Given the light-weight nature of such messages, leveraging spontaneously mobile devices owned by the survivors is one possibility. Moreover, opportunistic systems relying on mobile devices can fully leverage their intrinsic heterogeneous- and ubiquitous-nature. On the other hand, the rescue teams must be able to timely 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 devices¹ 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

¹ 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.

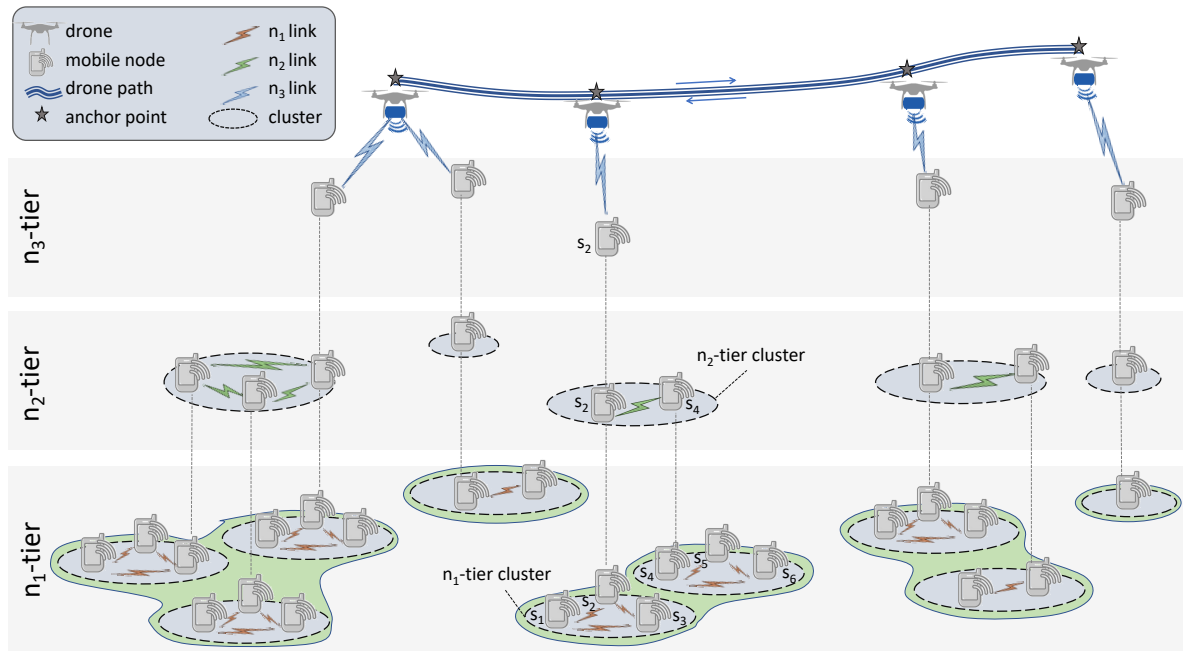


Figure 1. Multi-tier network architecture: (example of three communication technologies)

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 $r_{n_1} < r_{n_2} < r_{n_U}$ and
 141 energy consumption c as $c_{n_1} < c_{n_2} < c_{n_U}$. 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 δt 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.

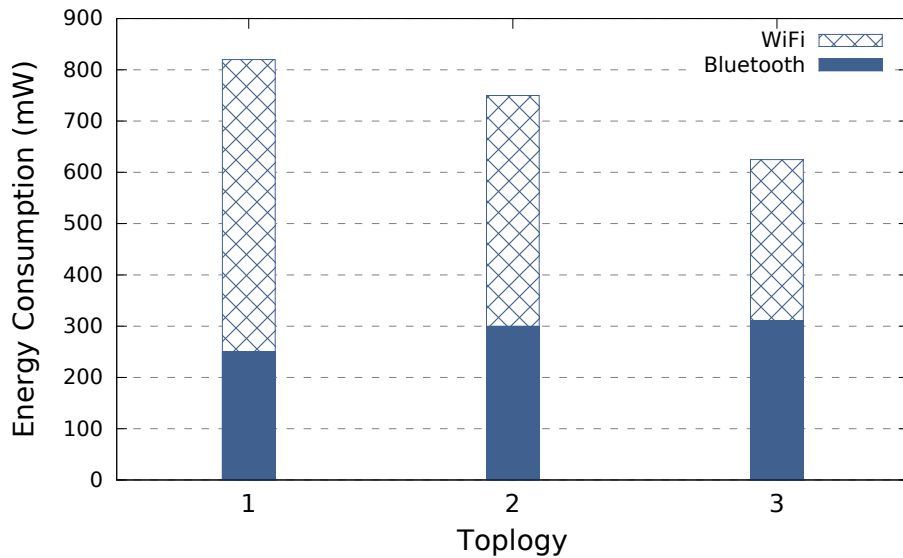


Figure 2. Energy consumption

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	≥ 100 m
Outdoor	50 m	≥ 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.

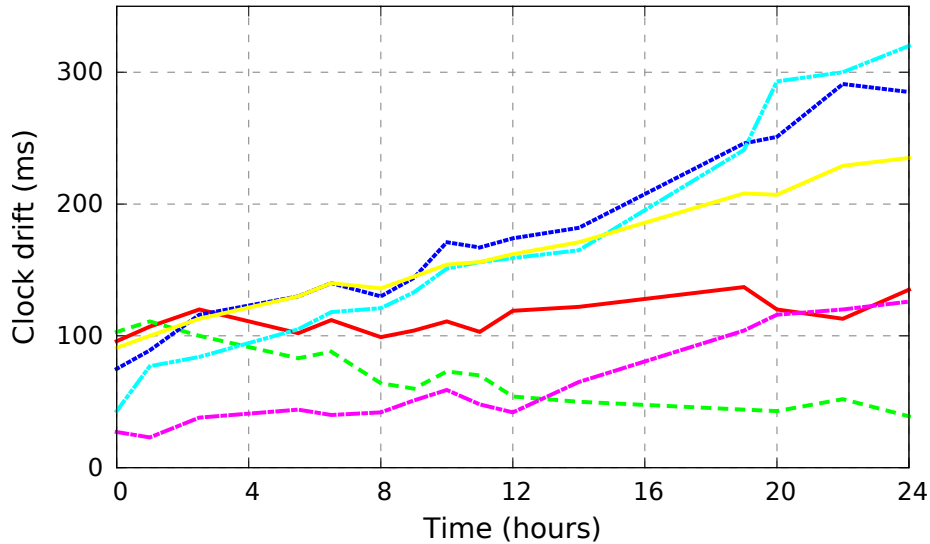


Figure 4. Smartphones clock drift

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].

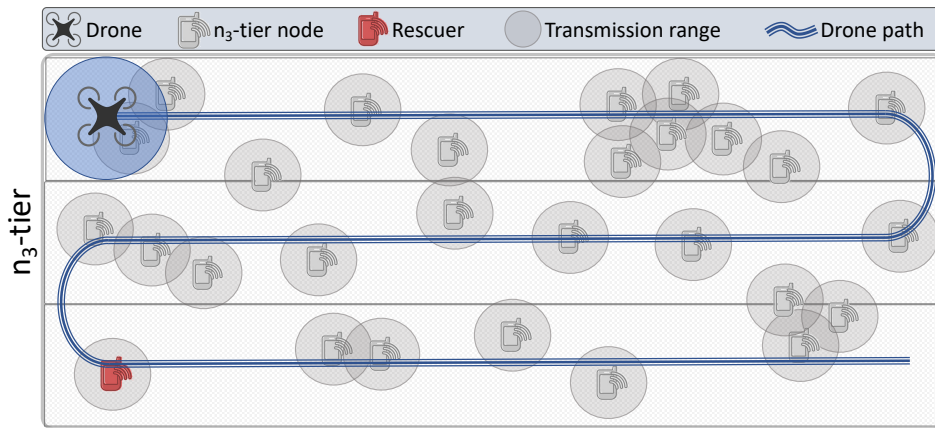


Figure 5. During the search phase a drone flies over the area affected by a disaster and stores the location of the discovered nodes in the highest (i.e., n_3) tier of the network.

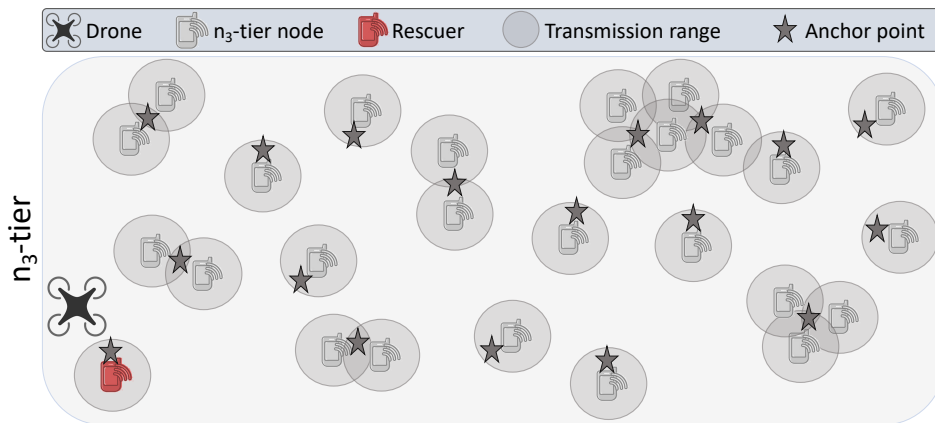


Figure 6. Drone anchor points shown with stars

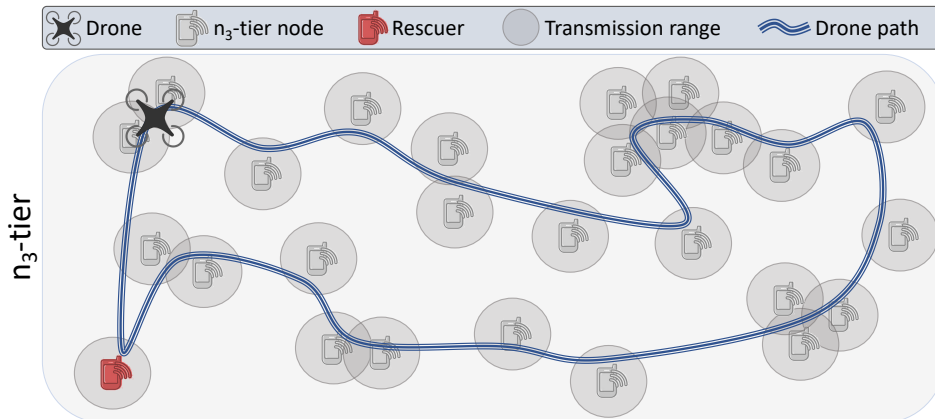


Figure 7. Shortest path for a drone to visit all the anchor points

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.

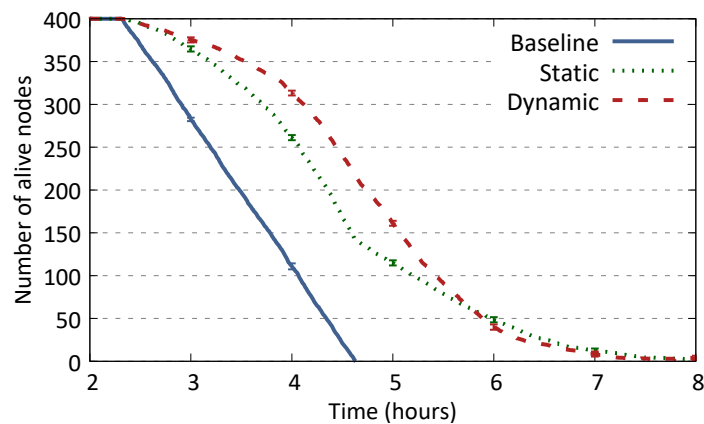


Figure 8. Number of alive nodes over time

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.

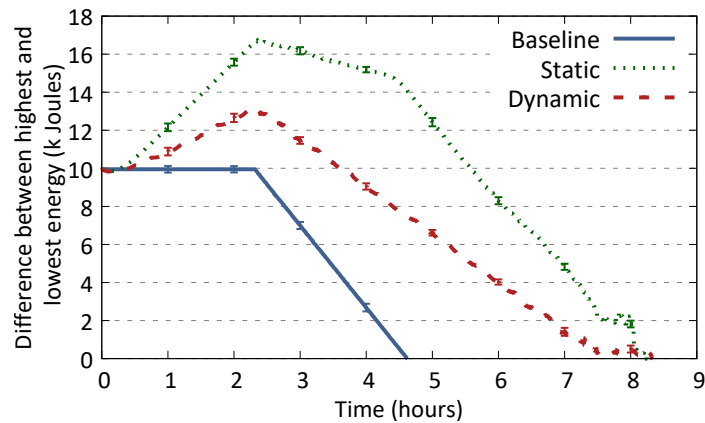


Figure 9. Difference between the highest and the lowest energy values in the network

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 ². 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

² <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.

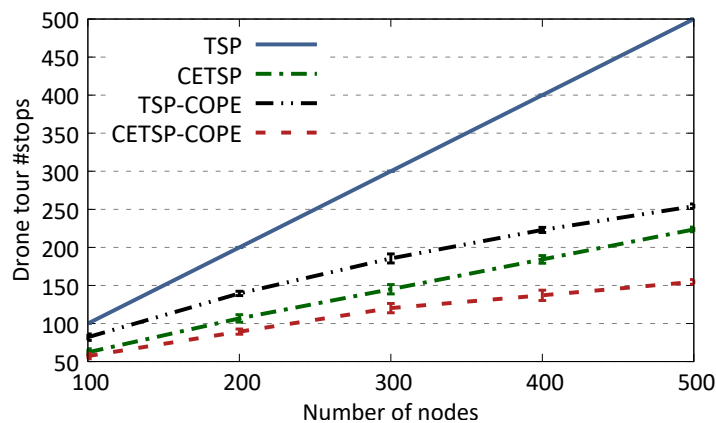


Figure 10. Number of stops

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,

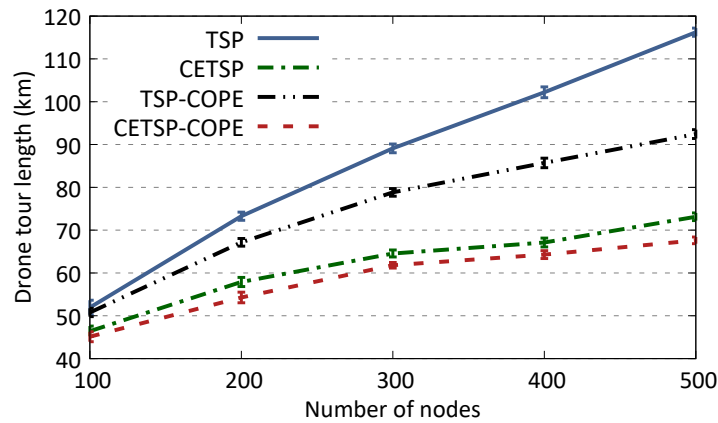


Figure 11. Tour length

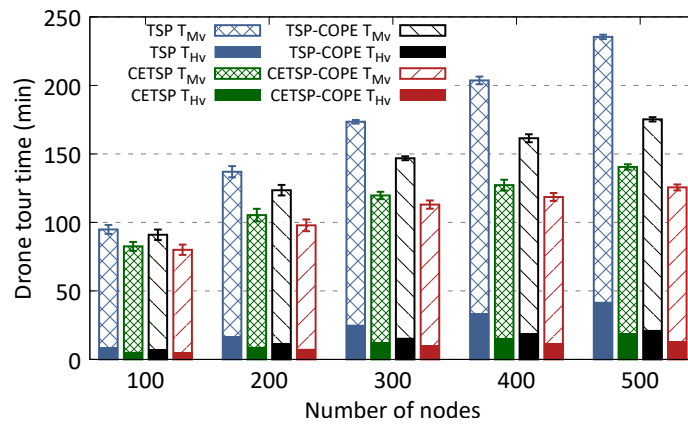


Figure 12. Drone hovering and flying time

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.

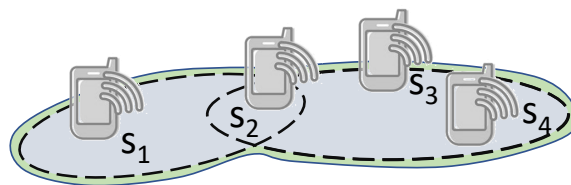


Figure 13. Example of clique multi-membership

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.

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