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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.

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

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

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

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

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.

2. Related works

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

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

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

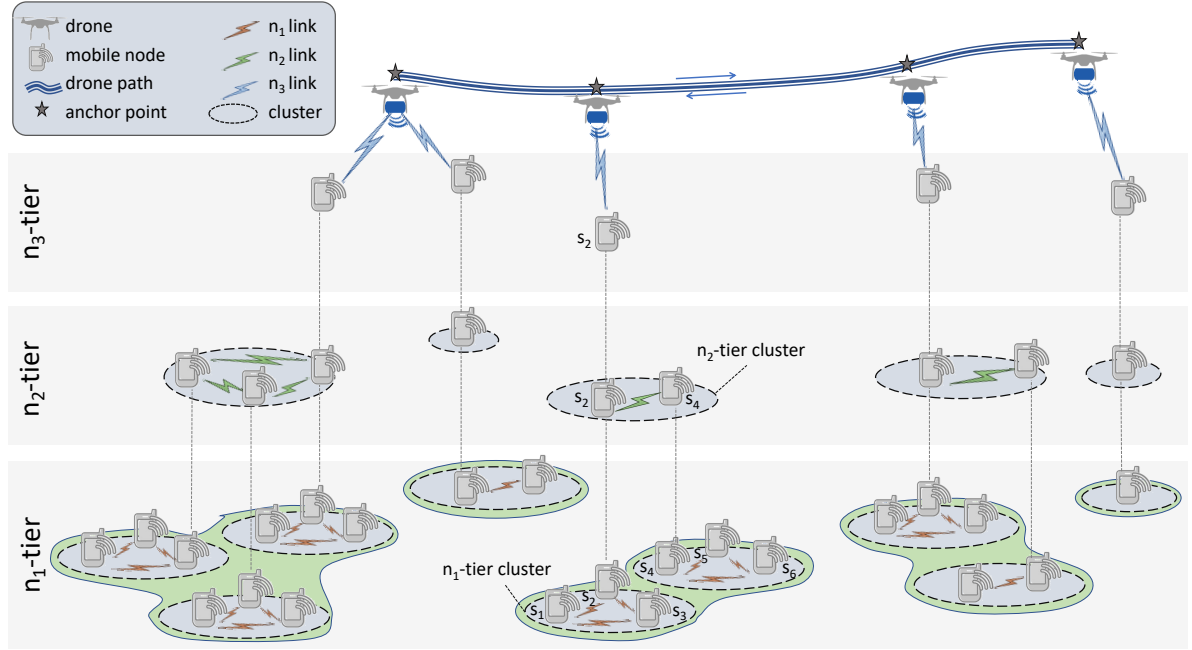


Figure 1. Multi-tier network architecture: (example of three communication technologies)

3.2. System Model

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

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

3.3. Multi-technology communication algorithm

A multi-tier communication heuristic is proposed that leverage the opportunistic connectivity of nodes at the different tiers to form clusters; CHs can then be designated to uniformly spread energy 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

```

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

4. Mobile devices performances: Smartphone use case

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

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

4.1. Energy consumption & Transmission range

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

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

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

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

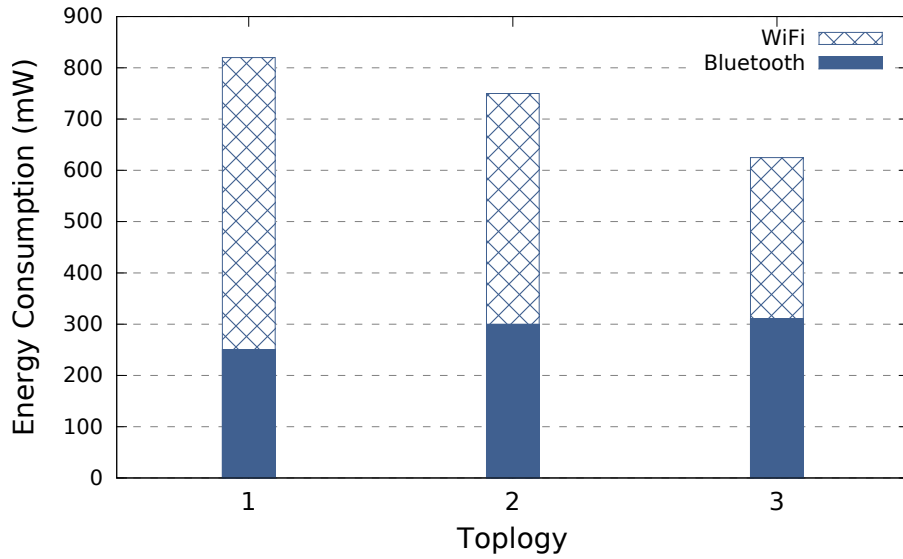


Figure 2. Energy consumption

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



Figure 3. Transmission range testing area

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

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

4.2. Clock Drift

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

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

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

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

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

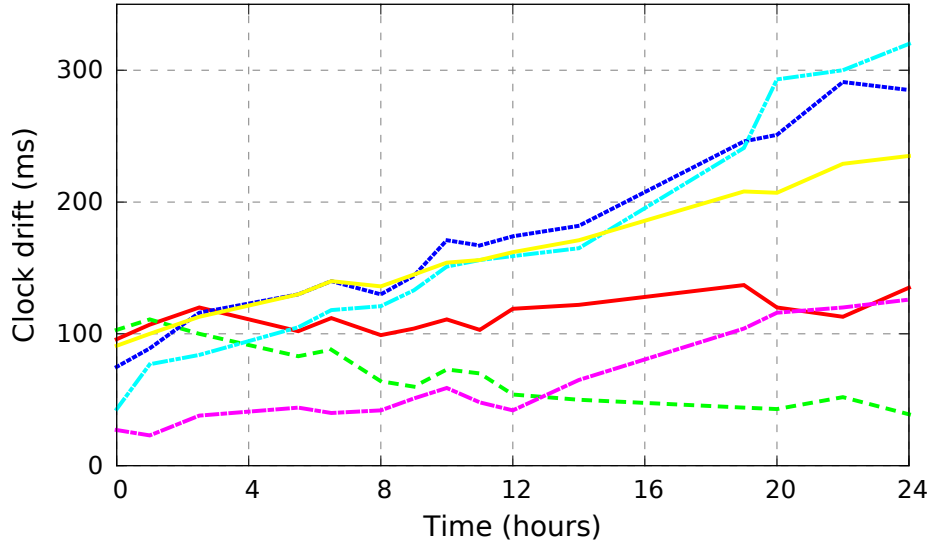


Figure 4. Smartphones clock drift

5. UAV Data Relaying

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

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

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

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

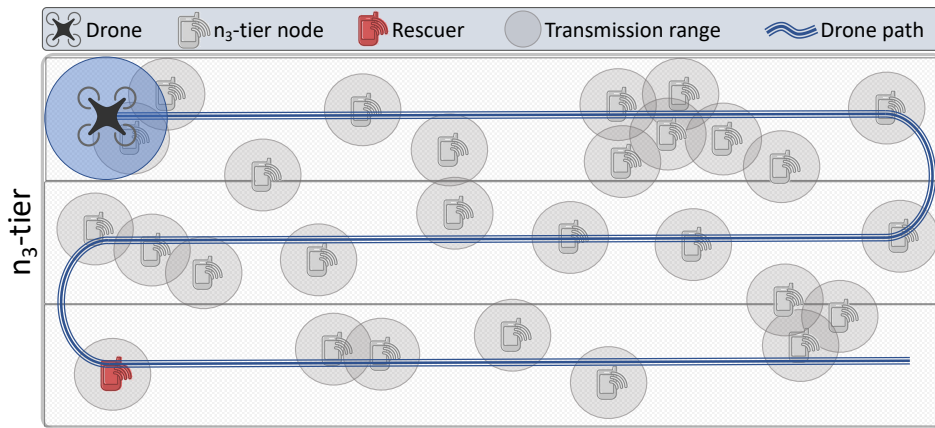


Figure 5. During the search phase a drone flies over the area affected by a disaster and stores the location of the discovered nodes in the highest (i.e., n_3) tier of the network.

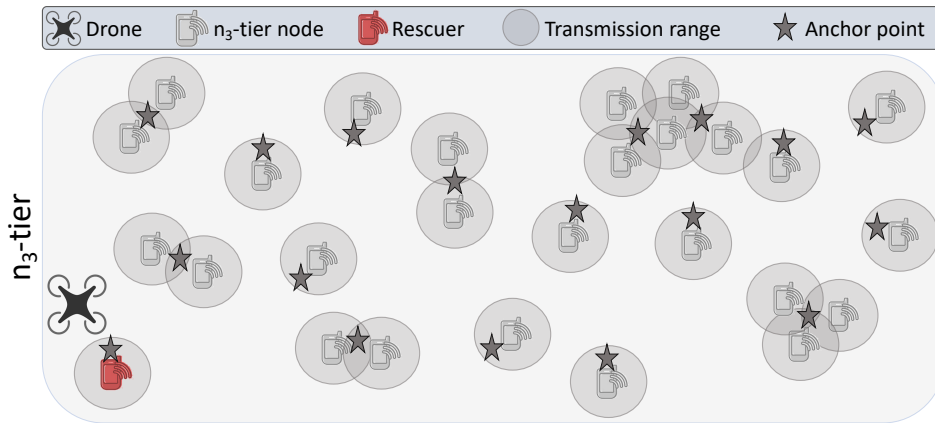


Figure 6. Drone anchor points shown with stars

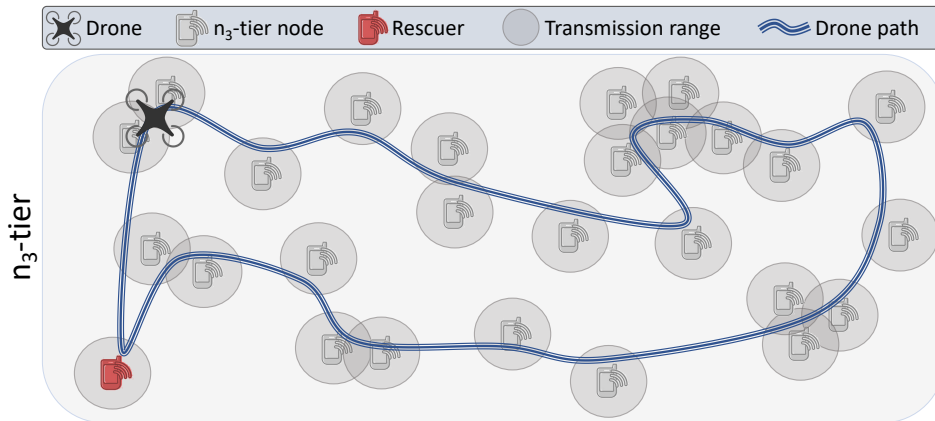


Figure 7. Shortest path for a drone to visit all the anchor points

Generally, the path is planned to reduce the drone's energy consumption of the drone. These algorithms aim to shorten the tour length, and yet the the time of a tour to collect the data from the nodes over a disaster area. More specifically, leveraging the cooperative communication and data relay protocol among the nodes underlying the UAV yields to reducing the number of points a drone should visit. In fact, identifying anchor points from which a drone can serve more than one node 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

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

6. Performance Evaluation

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

6.1. Cooperative Multi-tier Data Relaying

6.1.1. Methodology and Setup

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

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

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

6.1.2. Obtained Results.

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

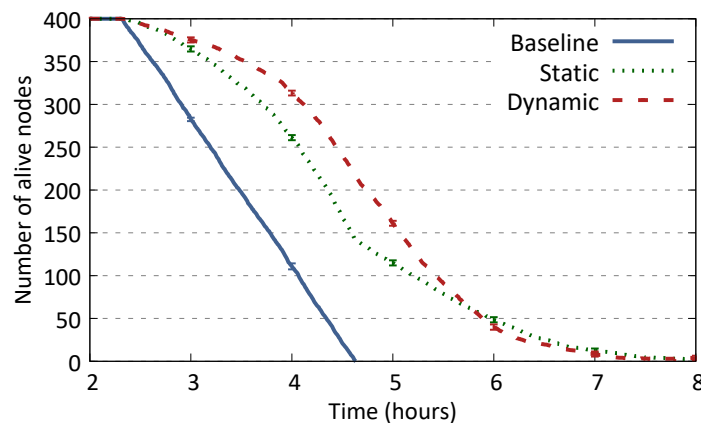


Figure 8. Number of alive nodes over time

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

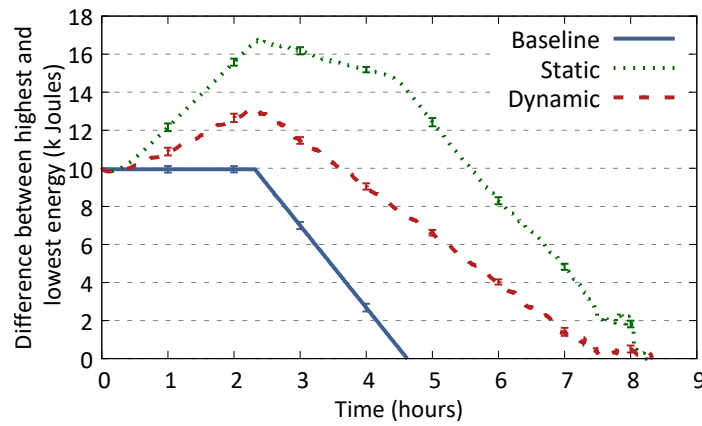


Figure 9. Difference between the highest and the lowest energy values in the network

6.2. Cooperative Data Relaying with UAVs

6.2.1. Methodology and Setup.

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

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

The following assesses and compares the performance of the two proposed TSP-COPE and CETSP-COPE algorithms (see Section 5) with the selfish TSP and CETSP algorithms. All the four schemes have been implemented as additional modules to the ONE simulator². The considered scenarios consist of various network densities, where the nodes are randomly situated in an urban area. A drone flies over the disaster area with a speed of 10 m/s. We assume that 2 s is a sufficient time to exchange data with a node, especially given the fact that the data, generally in disaster scenarios, consists of light-weight messages useful for rescue operations and assistance. However, we consider a *time-guard* of a minimum of 5 s for a drone to hover above a node. Moreover, the hovering time of a drone extends in proportion to the cardinality of the cluster that the node is CH of. For instance, a drone visiting a CH point of a cluster of three members would stop for a time of max (5 s, 6 s). We impose such time-guards to take into account for possible unsuccessful transmissions or collisions.

6.2.2. Obtained Results.

Figures 10, 11, 12 show the number of stops, the length, and time of a drone tour in terms of the 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/>

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

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

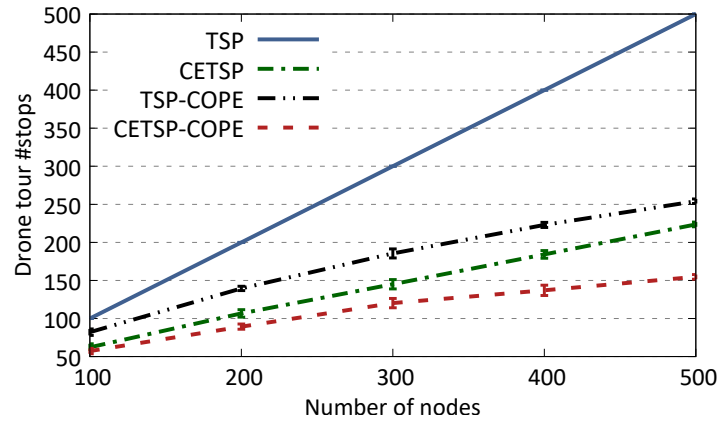


Figure 10. Number of stops

7. Open challenges and Future Directions

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

7.1. Survivor and rescuer mobility

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

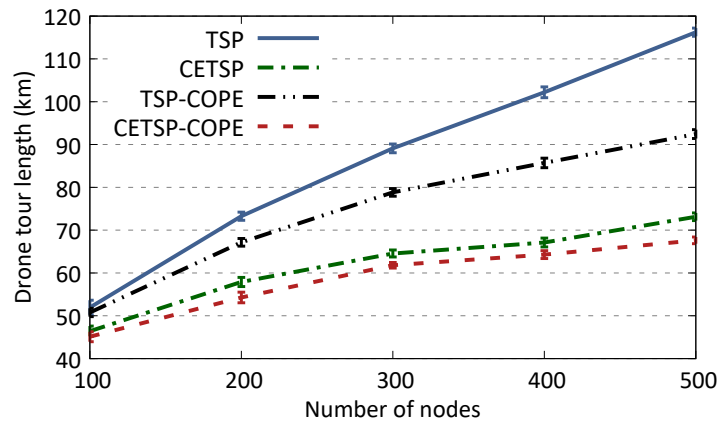


Figure 11. Tour length

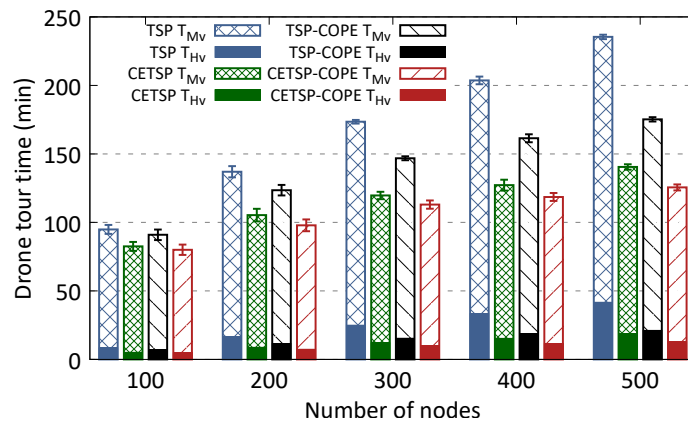


Figure 12. Drone hovering and flying time

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

7.2. Belonging to multiple cliques

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

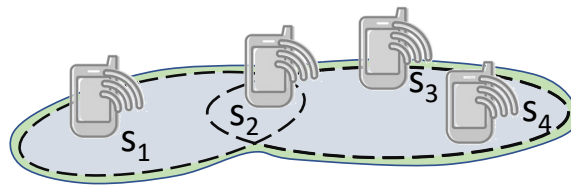


Figure 13. Example of clique multi-membership

7.3. Devices heterogeneity

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

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

7.4. Unavailability of some communication interfaces

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

7.5. Multi-drones

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

7.6. Dynamic 3D drones path planning

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

8. Conclusions

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

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

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