Opportunistic Disaster Recovery

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***Abstract*—Disaster scenarios require different recovery solutions such as evacuation guidance, to perform the right action for wounded persons and efficiency diffuse useful alert for locating trapped survivors. These latter are constrained mainly by the infrastructure-less environment caused by the disaster damage (e.g. storm, earthquake). Exploiting opportunistic communications to design recovery solutions presents a promising solution. However, several constraints are encountered, mainly, the multi-network assortment integrated in mobile equipment and the limited and various battery powers of mobile devices. This work presents a cooperative-based solution, COPE, that exploits the multi-network feature of mobile devices and takes the various power levels into account. COPE allows the coverage of a large area for a longer time while guaranteeing an important alert delivery.**

***Index Terms*—opportunistic communication, multi-network, energy consumption, disaster recovery**

I. Introduction

Opportunistic communications present an interesting way of communication after disasters such as flooding and earthquake [1]. Indeed, even though cellular network infrastructure might have been destroyed, mobile devices such as smartphones can be used for short-range based opportunistic communications and thus can offer several disaster recovery services [2], [3]. For instance, as shown in Fig. 1, survivors trapped inside buildings can exploit their smartphones to communicate with proximate rescuers using available communications (e.g. Bluetooth, Wi-Fi) to diffuse their location information and thus to speed up and ease their rescue operations.

Recent literature works [2–6] have proposed disaster recovery solutions that exploit opportunistic communications while some important features have been left behind. Indeed, they did not consider mobile devices equipped with multiple network technologies. However, nowadays, devices such as smartphones offer different network technologies (e.g. cellular, WiFi Direct, Bluetooth) and the interface selection is left to the user who cannot perform the efficient choice [7]. Moreover, mobile devices with various battery levels have not been considered which obviously have an effect upon the recovery solution performance.

This letter presents COPE, an opportunistic alert diffusion scheme useful for trapped survivors during disaster scenarios. COPE targets to rapidly reach proximity rescuers while maintaining devices alive for longer time. We first describe COPE scheme. Next, we present simulations results to demonstrate COPE effectiveness over energy consumption and alert delivery rates.

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Fig. 1. Opportunistic network in disaster scenario

II. COPE: Cooperative Opportunistic Alert Diffusion

This section describes COPE (**C**ooperative **OP**portunistic al**E**rt diffusion) scheme that considers multiple network technologies and various energy levels for alert diffusion during disaster events.

A. System model

The system model involves a set of mobile nodes $\mathcal{S} = \{s_i\}$ equipped each with a mobile device. This latter is characterized by a current power level p_{s_i} and is considered equipped with three network technologies (n_1, n_2 and n_3) corresponding respectively to those available nowadays in smartphones (Bluetooth, WiFi, Cellular). This work classifies the available network technologies according to their energy consumption *EC* and transmission range *TR* as follows:

$$\begin{cases} TR_{n_3} > TR_{n_2} > TR_{n_1} \\ EC_{n_3} > EC_{n_2} > EC_{n_1} \end{cases}$$

e.g. Bluetooth provides the shortest transmission range, thus consuming the lowest energy amount.

Additionally, mobile devices are considered with various initial battery power levels. A power threshold p_{th} is defined to distinguish low-power from high-power nodes (i.e. s_1 is considered a high-power node with respect to s_2 if their energy levels $p_{s_1} - p_{s_2}$ differ by more than p_{th}).

B. Multi-technology and energy-based communication

COPE aims to leverage all the available network technologies for the alert diffusion while preserving the battery power for as long as possible. Emergency alert presents a short message that mainly contains survivors position. Fig. 2 illustrates a multi-technology communication view of COPE.

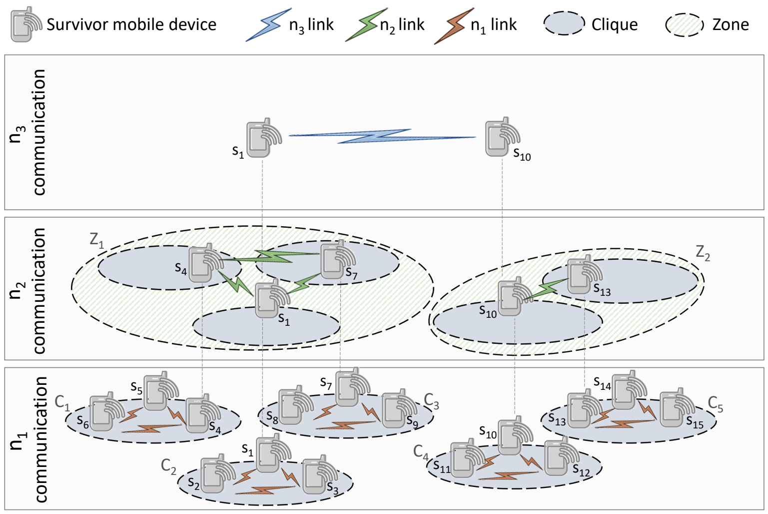

Fig. 2. Multi-technology communication overview

1) n_1 communication: nodes start diffusing the alert message and discovery neighbors using the less power network technology n_1. This latter is maintained permanently active and is privileged for communications between proximate nodes to preserve the battery power. For a cooperative alert diffusion, nodes exchange their 1-hop n_1's neighbors allowing the discovery of 2-hop neighbors, and cliques are then formed between proximate nodes as shown in Fig. 2-Layer n_1 communication (e.g. cliques C_1 and C_2). A clique $\mathcal{C}$ is defined as a set of nodes such that each node of the clique is directly connected to all the other nodes belonging to the same clique ($c_i \in \mathcal{C} \Leftrightarrow \forall c_j \in \mathcal{C}, c_j \in N(c_i)$).

2) n_2 communication: Inside each clique, a cooperative communication is performed based on the n_2 network technology. The following describes the communication from the network interface n_2 perspective which includes two main parts: the (i) wake-up schedule computation and the (ii) zone formation.

(i) n_2 wake-up schedule: inside each clique, nodes alternately diffuse the alert message and discover neighbors using the network technology n_2. Time is then divided into equal time-slots τ. Therefore, each node determines its wake-up schedule based on the clique information (IDs and energy levels of nodes belonging to the same clique).

With the support of high-power nodes, COPE aims to maintain low-power batteries hold for longer time. Hence, high-power nodes have a longer wake-up schedule than low-power nodes (participate for more time in the alert diffusion) allowing these latter to preserve their batteries for longer time. The ratio between the wake-up periods of low- and high-power nodes is not the focus of this work and we have simply assumed that high-power nodes have a wake-up period twice more longer than low-power nodes. Each node determines its wake-up period P_{up} during the time-slot τ based on the size of their clique and to their energy levels as follows (eq 1):

$$P_{up} = \tau / \sum_{i=0}^{\Omega_{\text{clique}}-1} E_{coef}(s_i) \tag{1}$$

$$\Omega_{\text{clique}} = \#\text{nodes belonging to the same clique}$$

$$E_{coef}(s_i) = \begin{cases} 2 & \text{if } s_i \text{ is a high-power node} \\ 1 & \text{else} \end{cases}$$

Then, the wake-up order is determined based on the node ID in comparison to those of nodes belonging to the same clique (i.e. node with the lowest ID occupies the first period during the time-slot). Hence, each node can determine the starting and ending of its wake-up according to the n_2 interface as shown in eq 2 and eq 3.

$$t_{up} = \sum_{i=0}^{id_{\text{rank}}-1} E_{coef}(s_i) \times P_{up} \tag{2}$$

$$t_{sleep} = \sum_{i=0}^{id_{\text{rank}}} E_{coef}(s_i) \times P_{up} \tag{3}$$

During its wake-up, each node activates its network interface n_2 for neighboring discovery and alert diffusion, otherwise, it switches to the power save mode.

In the case of overlapping cliques (i.e. a node is part of more than one clique), the wake-up schedule is computed according to the clique with a minimum number of nodes and is diffused inside the cliques to be taken into consideration for the wake-up schedule computation of other nodes.

(ii) n_2 zone formation: If a node i discovers other proximate nodes j from the n_2 network perspective (nodes i and j are neighbors with n_2 technology), together, they form a zone that includes their respective cliques (the zone is a clique at an upper level). For instance, as shown in Fig. 2-Layer n_2 communication, nodes s_{10} and s_{13} discover each other based on the n_2 network interface. Then, they exchange information (i.e. nodes IDs and energy levels) about their corresponding

cliques C_4 and C_5 and then form a zone Z_2 that includes their corresponding cliques C_4 and C_5. Afterwards, they diffuse the zone information (nodes belonging to the zone and their energy levels) to their cliques through the active interface n_1.

3) n_3 communication: : inside each zone, a cooperative diffusion can be performed from the n_3 communication perspective based on an alternative alert diffusion. Each node computes its wake-up schedule from the n_3 communication perspective by referring to its energy level and ID and those of nodes inside the same zone.

The network topology is dynamic due to leaving and joining nodes. This latter can be detected through the periodic messages exchanged between nodes belonging to the same clique/zone. When the topology changes, nodes exchange their 1-hop neighbors and update their cliques information and re-computes their wake-up schedules.

C. Discussion

We would like to emphasize that this work can be extended to a mobile network composed of nodes having each more than three network technologies (i.e. $\mathcal{N} = \{n_j \mid j \in [1..N]\}$). Indeed, proximate n_j nodes can form groups and cooperate based on the network technology n_{j+1} that offers a superior transmission range.

COPE can also be suitable for a network environment involving mobile devices equipped each with a single network technology that can be managed by different transmission powers offering thus different transmission ranges and energy consumptions.

COPE is suitable to a network environment that is very dynamic. However, this latter will lead to a frequent exchange of topology update messages to re-compute the wake-up schedules. It is important to study the impact of the network dynamicity on the alert diffusion scheme mainly in terms of energy consumption which presents a focus of our future work.

D. Example of motivation

Fig. 3 depicts a simple scenario featuring 7 nodes equipped each with a mobile device having 3 network technologies n_1, n_2, and n_3 providing, respectively, low, medium and high transmission ranges and corresponding to low, medium and high battery power consumption. It considers survivors trapped in two proximate locations (e.g. buildings). This example assumes equal initial energy level for all nodes except node s_5 is considered with high initial energy level (i.e. $p_{s_5} - p_{s_i} > p_{th}$ where $i \in [1..7] \setminus \{5\}$).

We suppose that survivors use COPE and could initially form two different cliques $C_A = \{s_1, s_2, s_3, s_4\}$ and $C_B = \{s_5, s_6, s_7\}$ using network interface n_1. Inside clique C_A, using network interface n_2, nodes cooperate alternately to diffuse the alert message and discover n_2-neighbors during a wake-up period of $\tau/4$ (i.e. τ divided by the number of nodes inside clique C_A). Indeed, nodes inside C_A will have equal wake-up periods since they have similar energy levels. On the other side, since nodes inside clique C_B have various energy levels, they diffuse the alert message and discover n_2-neighbors during a wake-up period of $\tau/4$ except node s_5 for a wake-up period of $2\tau/4$ (i.e. since s_5 has a high power level, it participates two times more than s_6 and s_7).

Assuming that nodes s_1 and s_5 could discover each other using the interface n_2. Hence, they form a zone Z comprising cliques C_A and C_B and they diffuse the zone information to the nodes inside the same clique using interface n_1. Knowing the topology of the formed zone and based on interface n_3, nodes cooperate alternately for the alert diffusion during a wake-up period of $\tau/8$ each except s_5 for $2\tau/8$.

This simple scenario shows the considerable energy saved compared to the individual-based diffusion (i.e. selfish) in which each survivor only counts on himself/herself for his/her survival. Indeed, nodes belonging to cliques C_A and C_B can save, respectively, approximately 75% and 66% of battery power, with respect to n_2 communication. Similarly, nodes inside cliques C_A and C_B can save approximately 85% of energy regarding the n_3 communications. This allows mobile devices batteries to be preserved for longer time and thus increase the chance of reaching rescuers.

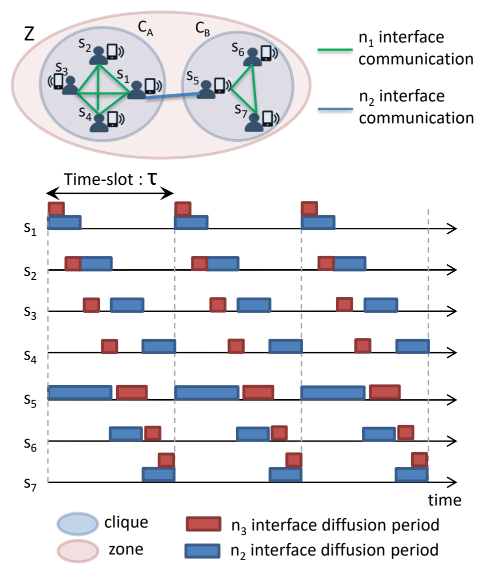

Fig. 3. Simple scenario

III. Evaluation

A. Methodology

COPE performances have been evaluated by simulations conducted through the Opportunistic Network Environment (ONE) [8]. Simulations considers 35 survivor-nodes. Bonn-Motion mobility generator was used to generate the nodes movement specific for disaster scenarios [9]. Simulation scenarios consider 7 incident locations (e.g. parking, building) in which survivor-nodes are randomly distributed. Conducted simulations consider survivors equipped each with a mobile device having 3 network interfaces n_1, n_2 and n_3 corresponding to low, medium and high transmission ranges (10 m, 50 m and 200 m) and to low, medium and high battery power consumption. It is assumed that n_3 (n_2 respectively) transmissions consumes 3 times (2 times respectively) more energy than n_1 transmissions. The energy level is expressed in terms of energy units. Each mobile device has an initial battery power assigned randomly in the range of [10 k,20 k] energy units. The power threshold p_{th} has been set to 500 energy units. The time-slot τ has been fixed to 60 seconds during testing scenarios. We would like to emphasize that the considered scenario can be similar in practice to survivors equipped with smartphones having 3 network technologies (Bluetooth, WiFi and Cellular). Instead of diffusing individually the alert message using all the network technologies, survivors can cooperate based on the bluetooth technology and diffuse alternately the alert message using the WiFi and cellular technologies.

B. Energy saving

COPE is compared with selfish and clique-based cooperative alert diffusion schemes. The former is based on an individual alert diffusion. The survivor can either use many network technology of his mobile devices or s/he can use the most useful ones (e.g. interfaces with highest transmission range). The latter consists of cooperative diffusion limited to neighbors discovered from the low-power network technology perspective. Fig. 4 illustrates the average power consumption of the different alert diffusion schemes over time. Selfish diffusion results in quick battery drain (average lifetime of 3h30 and 4h considering 3 and 2 network technologies respectively) which is not efficient since rescue operations might take long time. Cooperative-based diffusion allows the battery to hold up to approximately 10 and 12 hours for clique-based and COPE, respectively.

C. Energy consumption reduces with the network density

We evaluate the alert diffusion schemes considering various network density. As illustrated in Fig. 5, as the network density increases as the battery consumption decreases since more nodes will cooperate and hence be in sleep mode for longer time. On the other side, selfish-based diffusion in independent from the density since it is based on an individual diffusion.

To approve the previous results, the following sections evaluate COPE in terms of alert delivery success ratio. Other than preserving the battery power, alert diffusion schemes should guarantee the emergency alert delivery to proximate rescuers moving around the disaster area.

D. Guaranteeing alert delivery

In the following, simulation considers a mobile rescuer-node moving in proximate of the disaster area with 100 various random paths at different moments of the simulation. Simulation results evaluate the successful alert messages that have reached the rescuer and compare COPE, Selfish and equality-based alert diffusion. Equality alert diffusion method operates similarly to COPE but does not consider the various energy levels. Indeed, based on Equality, nodes belonging to the same clique/zone cooperate for equal period of times. Simulations scenarios consider two period of times to evaluate the alert delivery success: (i) the period $[0, 1h30]$ during which all nodes still have battery power (see Fig. 4), thus to make a fair comparison with the selfish diffusion and (ii) the period $[7h, 12h]$ (see Fig. 7) to show the impact of considering the various energy levels on the alert diffusion scheme.

Fig. 6 illustrates the alert delivery success rate considering a rescuer that moves with various paths during the period $[0, 1h30]$. Results show that all the alert diffusion schemes succeed to deliver the emergency alert to the rescuer when this latter has a low velocity (i.e. walk 1-1.5m/s and running 2-4 m/s speeds). As the rescuer speed increases (6-8m/s and 12-14m/s), the alert delivery ratio decreases considering cooperative alert diffusion methods. Indeed, a rescuer-node can enter and leave the coverage of a sleep-node before its wake-up. Even though rescuer high speed is not realistic during disaster, cooperative diffusion methods can mange this situation by reducing the time-slot enabling fast switching between sleep and active modes. A further study to determine the efficient time-slot size for the cooperative alert diffusion scheme is a focus of our future work. On the one hand, a short time-slot may affect cliques comprising a high number of nodes. Considering a short time-slot (e.g. $10\ s$) and a clique of high number of nodes (e.g. 10 nodes), nodes' wake-up is too short ($\sim\ 1\ s$) according to COPE. However, a short wake-up period might be not enough to discover neighbors and diffuse the alert message. On the other side, a long time-slot may have an impact on cliques with a small number of nodes. In fact, a node can be in sleep mode for a long period of time during which a potential rescuer might enter and leave its coverage before its wake-up. Hence, the time-slot can be computed considering different features such as rescuer velocity and number of nodes inside a clique/zone.

The following section aims to show how the consideration of various energy levels impacts the alert delivery ratio.

E. Think about low-power nodes

Since nodes with high energy-level participate in the alert diffusion for longer time, COPE allows nodes with low energy-level to stay alive for longer time. Indeed, as shown in Fig. 7, considering COPE, nodes batteries start to get empty after 10.5 hours. On the contrary, considering equality-based diffusion, nodes with low energy can live for much less time (approximately 8 hours). Therefore, considering the various energy levels, COPE maintains a large network coverage by maintaining the maximum number of nodes alive as long as possible. This leads to waste few minutes from the batteries lifespan of high-power nodes allowing low-power nodes to gain few hours of battery lifetime and consequently to maintain a large network coverage for longer time.

To show the impact of considering the various energy levels, simulations were conducted to consider 100 scenarios involving a rescuer-node that moves with random path during the period of time $[7h, 12h]$ (see Fig. 7) where only some nodes have energy left. Fig. 8 shows that COPE clearly outperforms equality with respect to the alert delivery success ratio. This is because COPE allows a maximum network coverage for

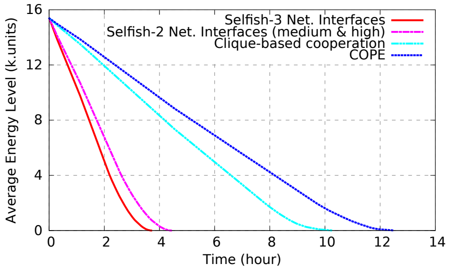

Fig. 4. Average energy level

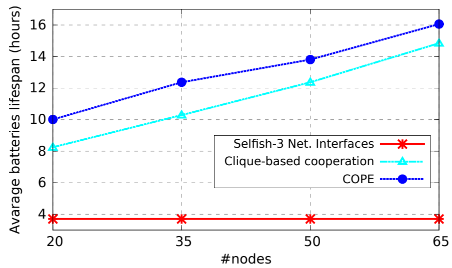

Fig. 5. Average batteries lifespan

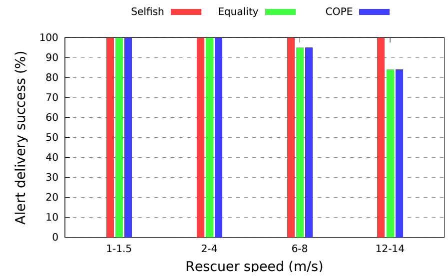

Fig. 6. Alert delivery success rate (all nodes alive)

longer time by considering the various energy levels and thus allowing low-power nodes to stay alive longer.

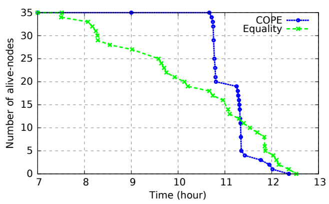

Fig. 7. Network nodes disappearance due to lack of battery

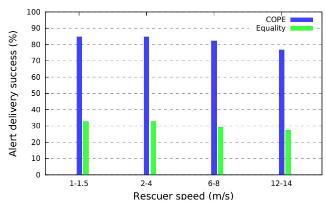

Fig. 8. Alert delivery success rate where some nodes are still alive

IV. Conclusion and on-going work

This work proposes a novel alert diffusion scheme, named COPE, that exploits opportunistic communications and considers mobile devices that come with different network technologies and have various initial battery powers. COPE allows mobile devices to preserve their batteries and thus to stay alive for as long as possible and it guarantees the emergency alert delivery to proximate rescuers.

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