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Human-centric wireless sensor networks to improve information availability during urban search and rescue activities

Sergio F. Ochoa [a,*], Rodrigo Santos [b]

[a] Department of Computer Science, Universidad de Chile, 2120 Blanco Encalada Av., CP 837-0459 Santiago, Chile
[b] Department of Electrical Engineering, Electrical Engineering Research Institute, Universidad Nacional del Sur, CONICET, 1253 Alem Av., CP 8000 Bahia Blanca, Buenos Aires, Argentina

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ABSTRACT

When a natural disaster hits an urban area, the first 72 h after are the most critical. After that period the probability of finding survivors falls dramatically, therefore the search and rescue activities in that area must be conducted as quickly and effectively as possible. These activities are often improvised by first responders, stemming from the lack of communication and information support needed for making decisions in the field. Unfortunately, improvisations reduce the effectiveness and efficiency of the activities, in turn, affecting the number of people that can be rescued. To address this challenge, this article introduces the concept of a human-centric wireless sensor network, as an infrastructure that supports the capture and delivery of shared information in the field. These networks help increase the information availability, and therefore, the efficiency and effectiveness of the emergency response process. The use of these networks, which is complimentary to the currently used VHF/UHF radio systems, was evaluated using a simulated scenario and also through the feedback provided by an expert in urban search and rescue. The obtained results are highly encouraging.

1. Introduction

Every year natural disasters, such as earthquakes, hurricanes, volcanic eruptions and tsunamis, hit urban areas. During the first 72 h after the event, usually known as the "golden relief time", the response process is focused on searching and rescuing people [1]. The probability to find survivors after that time is increasingly low [2]. Coburn et al. [3] report the evolution of the survival rate over time, by analyzing the results of four earthquakes (Fig. 1). The analysis indicates the survival rate does not evolve in the same way in every extreme event; however, it is clear that the first 72 h after the occurrence are the most critical ones to search and rescue efforts. Similarly, after studying the survival rate in earthquakes, Fiedrich et al. [4] proposed a model to estimate such a rate (Fig. 2). The prediction model also indicates that the first 72 h are the most critical for rescuing survivors. Therefore the SAR activities must be quick and effective, because the number of survivors is directly related to such efficiency.

Several types of first responders participate in this process, for instance firemen, medical personnel, police officers and military units, who are grouped in teams and deployed to the affected area. In particular, firefighters and military units are usually trained to guide these teams. They typically use VHF/UHF radio systems to support the communication in the field and thus try to coordinate their activities.

These communication systems have shown to be easy to deploy and also reliable in supporting rescuer interactions when the regular communication infrastructure of the affected area is not available. Particularly, UHF radio systems can work as a multi-hop network, which extends their communication threshold and improves their capability to connect teams in the field. In spite of this, the use of these radio systems often leaves teams isolated because of the limitations imposed by their communication links [5–8]; for example the number of communication channels are typically not enough to support the communication in the field, the messages delivered by a radio device are frequently overwritten by messages delivered by more powerful devices, and often the messages are not understandable because they were mixed with others that were transmitted at the same time. If a SAR team has to wait an extensive time period to access a communication channel during the golden relief time, it is highly probable that the commander decide to improvise their actions/decisions because in such a period every minute counts. Several researches indicate that the response process during the golden relief time is improvised, due lack of communication and information support for making decisions in the field [6,9–11].

Trying to deal with this issue, some communication requirements [12] and architectures have been proposed [5,13]. Moreover,

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[*] Corresponding author. Tel.: +56 2 9784879; fax: +56 2 6895531.
E-mail addresses: sochoa@dcc.uchile.cl (S.F. Ochoa), ierms@criba.edu.ar (R. Santos).

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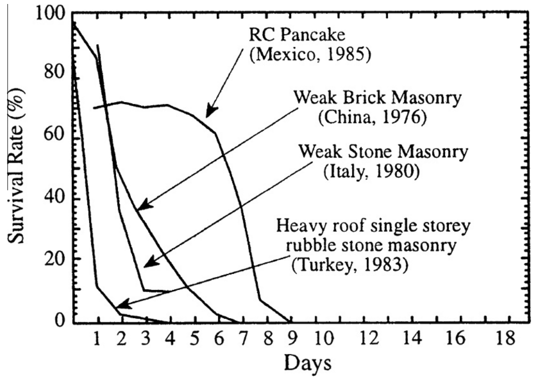

Fig. 1. Real survival rate [3].

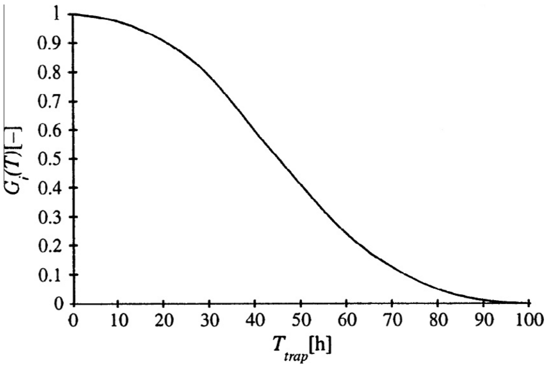

Fig. 2. Estimated survival rate [4].

communication standards have been defined to address the stated problems, for example TETRA (Terrestrial Trunked Radio) [14] and TETRAPOL [15], and also several IT platforms that adhere to these standards have been implemented. These technologies are useful in practice, however their acquisition involves a cost that is not affordable (at least in the short-term) for firefighting organizations of many countries. Particularly, this is the case of Latin American countries where firefighters are almost exclusively volunteers, and they receive minimal economical support from their governments.

The authors hypothesize that *human-centric wireless sensor networks (HWSN) can contribute to the improvement of the information availability during SAR activities,* and thus increase the efficiency and effectiveness of the process. The HWSN combines regular and human-based sensing devices that interact among them to reach a pre-established common goal, e.g. increase the information availability in a physical area. Therefore, these networks can be considered as collaborative and multi-sensor. Because these networks involve regular technology, their cost would be more affordable for volunteer firefighting organizations than modern radio systems (e.g. those based on the TETRA or TETRAPOL standards). The HWSN, which are complimentary to VHF/UHF radio systems, involve a minimal effort to be deployed in the field. Therefore, they could be used to support the teams from the beginning of the SAR activities.

These networks could also be used to increase the information availability in work scenarios where there is little or no communication support, and where mobile workers act as information fusion agents. Examples of these work scenarios include underground mining jobs or massive health campaigns in isolated areas.

The definition of a HWSN is based on the formalization of an opportunistic network done by the authors in a previous work [16]. This article extends such a definition by describing the elements that are part of a HWSN, the way in which they interact and the strategy used by the nodes to share information through the network. The article also presents a simulated search and rescue scenario that allows us to compare the performance of the SAR process using both the regular supporting tools and the proposed HWSN.

The next section explains the basic structure of a SAR process. Section 3 presents the related work. Section 4 describes the structure and components of a HWSN. Section 5 formalizes the information delivery in a disaster area, using two well-known routing protocols on a HWSN. Section 6 presents a simulated search and rescue process and elaborates on the obtained results. Section 7 presents the conclusions and future work.

2. The urban search and rescue process

The international SAR protocol for urban areas establishes that this process must be conducted by teams [17]. Each team has a leader that makes the local decisions, assigns activities to the team members and coordinates the team actions with the incident commander (i.e. the main decision maker in the field) that is usually located in a command post. Most first response efforts are coordinated by firefighter companies since they are trained to guide such activities, they are usually located in the affected area (or close to it), and the emergency response is part of their mission. The SAR process conducted by these companies involves four major activities:

1. The commander in charge of a company establishes a *search area.* Such an area is typically a 2 × 2 or 3 × 3 square of blocks, which helps to minimize the communication problems in the field.
2. Immediately after that, the commander establishes the *command post* in a safe place inside or within the border of the search area. Everyone participating in the SAR process must know where the command post is located due this is the main coordination point for a company.
3. The commander organizes the first responders in two types of teams: scout and rescuers. A *scout team* involves three or four people and they are in charge of searching a sub-area for trapped survivors. The *rescue teams* complete the task by rescuing people identified by the scouts.
4. The teams perform the search and rescue of victims in a parallel way. The scout teams provide information to the command post about the search result in the sub-area, and the rescue teams retrieve such information from the command post to directly access the buildings with trapped victims.

Fig. 3 shows a search area being explored by a first response company composed of 43 members grouped in seven teams: 4 scout teams, 2 rescue teams and the command post. Every team has one or more coordinators that make local decisions and keep the command post informed. For operational reasons, the number of scout teams is usually more important than the rescue teams. Once the scouts have completed the work in a search area, they can be grouped to form new rescue teams, and thus to help other teams in such activities. When the company has finished the task, it moves to another search area. Then, the commander can keep or redefine the original composition of these teams.

The coordination of activities inside these teams (and also interteams) is typically supported two or three VHF/UHF radio channels [7]. It means that just two or three people can be speaking by radio at the same time, which is not sufficient for monitoring high risk activities. The number of available radio channels can be even low-

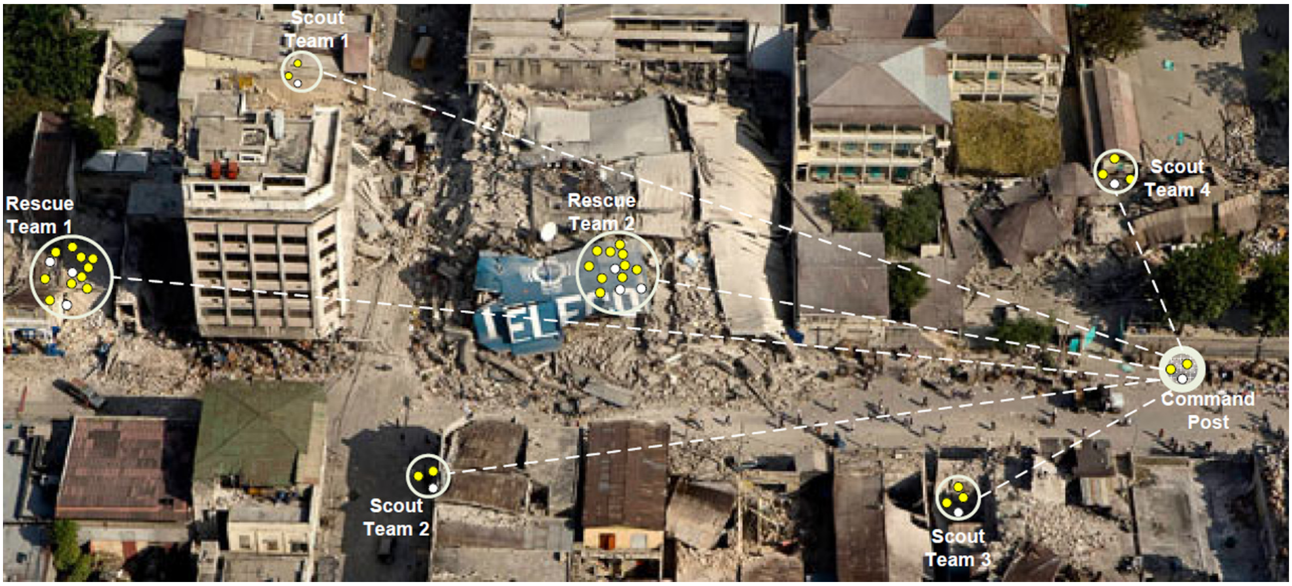

Fig. 3. Search and rescue teams in the field.

Fig. 4. Marking containing information about victims.

er because they are also affected by the problems mentioned in Section 1. For that reason, first responders typically exchange information during the search and rescue process through face-to-face meetings.

Every team has to keep its own annotations about the process [18]. The teams also use particular marks on buildings and structures indicating information about victims, as shown in Fig. 4. These symbols follow a standard nomenclature defined by the International Search and Rescue Advisory Group [17], and they allow other teams that arrive to the area to be informed of the status of a certain physical infrastructure (e.g. a building or a house).

A "V" is marked near the location of known or potential victims, with an "L" indicating the number of live victims, and a "D" for dead victims. The "V" has an arrow beside it when the location of a victim has been confirmed visually, vocally or through identified sounds. If there are only dead victims, the "V" is crossed out. Firemen circle "V" when all the victims have been removed from that area.

This marking protocol is well known by the international task forces, and therefore it represents a common language for all SAR teams. This kind of annotations on the search sub-area map is the typical information shared by the teams and the command post. The physical marks on the infrastructure are the only information that remains available after a company leaves a search area.

When another first response company arrives to the area, its commander needs to respond as quickly as possible to the first question: *Has a SAR team already explored this area*? In case of an affirmative response, two additional questions arise: *What are the limits of this search area*? and *What is its status*? The simplest way to respond to these questions is to send scout teams to explore the area and retrieve such information. Due to such activity is time consuming, most commanders prefer to continue moving until they find an unexplored area. This search for an unexplored area without a clear guideline represents one of the most important factors affecting negatively the efficiency and efficacy of the SAR process.

3. Related work

During the last years the scientific community has been working hard to deal with the limitations on communication and information sharing in disaster areas [5–7,19,20]. Both limitations are intrinsically related, since the lack of information in the field is in part a consequence of the limited communication support for SAR teams.

Trying to deal with this issue, the US Department of Homeland Security has introduced the "System of Systems" [12], which defines communication requirements and also a network architecture to be considered by IT solutions supporting first responder communication during disaster relief efforts. Some interesting proposals to implement such a recommendation have been reported [5,13]. Moreover, communication standards (e.g. TETRA [14] and TETRAPOL [15]) have been defined, which could help address the stated problems. As was discussed earlier, the IT solutions based on these proposals are not economically affordable (at least in the short-term) for many firefighting organizations.

Over the last few years, several researchers have proposed solutions that try to provide extra communication support in the affected area, and thus to improve the available information, the activities coordination and the decision making in the field. Most of these proposals address specific problems or particular search and rescue scenarios, and therefore they are not always appropriate to be applied in an urban SAR process after a disaster. For instance, an autonomous communication infrastructure was proposed by McCarthy et al. [21] to support mountain search and rescue after avalanches. Such a proposal involves the use of a Mobile Ad Hoc Network (MANET) to share information among members of a rescue team. The information sharing among teams requires the use of satellite or cellular networks. This requirement makes the proposal unsuitable to be used in massive urban search and rescue processes, since it is unlikely to count on access to a wide area network (WAN) in the affected area after a disaster. For the satellite communication usage, the first responders require special equipment, which also limits the suitability of that proposal.

Most mobile solutions designed to support first responses in small or medium-sized urban emergencies, and that could be expanded to deal with large emergency situations, have the same limitation (i.e. they require access to a WAN). Examples of the systems have been described in Barrado et al. [22], Braunstein et al. [9], Monares et al. [7] and Schöning et al. [11].

Another strategy used overcome the lack of communication support in a disaster area has been to deploy mobile antennas (e.g. for WiMax or GEO Satellite communication) in the affected area [23,24]. This strategy has mainly three limitations: (1) it requires an important time slot for transportation and set up, (2) the antennas must be deployed in an area where first responders are doing search and rescue, which is not easy to know during the first 72 h, and (3) they require expensive equipment that is not affordable for first responders in most countries. Therefore these solutions would be more appropriate to support recovery processes after a disaster than SAR processes.

The use of a lightweight and easy to deploy infrastructure has been recommended by some researchers to support information dissemination in the field during disaster relief efforts [25,26]. Typically these proposals use a MANET with routing capabilities. Although this strategy would help to increase the information availability inside a company, such proposals do not address the challenge of increasing the information availability inter-group, which is one of the most important issues affecting the efficiency and effectiveness of the large urban SAR processes.

There are also various research efforts that try to improve the operational conditions of the command post and particularly the decision making process done by a commander. For example the m-ARCE system provides an ubiquitous mobile office to manage disaster relief efforts [27]. Moreover, first responders, that are also users of the system, can exchange information with the mobile office. The m-ARCE system, which is still in the design phase, requires a reliable wireless network to support the message exchanges, though this is highly unlikely in a disaster area.

Bartels et al. [18] propose a different strategy to implement the command post using mobile computing devices, a MANET and information represented in a standard format. Such a proposal addresses just the information availability for a company. Similar to other proposals, it does not deal with the inter-group information availability.

Lorincz et al. [28] introduce an infrastructure named CodeBlue, which is based on wireless sensor networks, to assist rescuers in disaster response scenarios. The authors propose the integration of handheld devices into medical, disaster response and emergency care scenarios through the use of a particular communication protocol and a software framework that eases that process. The authors also propose the use of some particular sensors for vital signs, such as a pulse oximeter and a two-lead electrocardiogram monitor, which can support the first aid activities. These sensors can be conveniently attached to a handheld device when such information needs to be sent to a health center. Moreover, the usage of small RF-based location tracking devices is suggested for the monitoring of the rescuerś position in the disaster area. Using CodeBlue in practice requires active participation of the rescuers; e.g. for the placement of the sensors, and also in gathering/transmitting information from such devices. This represents a limitation of the solution for using it during the "golden relief time", as in such a time frame the rescuers are not able to be attentive to the sensors or devices. In stressful situations, the rescuers are typically aware of the sensors just when they require additional information to make a decision.

There has been important research conducted in routing strategies for delay-tolerant networks, which could be used to support information dissemination in a disaster area. Particularly, the geo-routing protocols seem to be suitable since the route and destination of a message could be adjusted according to the physical location of the participating nodes [29–31]. Similarly, routing protocols for vehicular networks [31,32] could also be considered to disseminate information in the field. However these protocols do not support real-time communication (i.e. they do not guarantee that a message will be delivered before a deadline), due they were not proposed to particularly disseminate information during SAR processes. This is an important limitation that makes them unsuitable to support this activity, due the information must arrive to the destination team while it is still working in the search area.

Agent-based approaches could also be used to share information in the field. For example Buford et al. [19] propose a distributed and cooperative agent-based model, designed to support highly reactive applications that share information. The agents interact with one another using multi-hop peer-to-peer overlays network, which provides a high scalability to the solutions. Clearly this approach could be considered to address the stated problem, although its limitations must be studied carefully. Similarly Fortino et al. [33] propose an agent paradigm and technology that is suitable for developing cooperative solutions based on WSNs. These proposals could be adapted and then used to support node interactions during SAR activities. The adaption process must consider supporting the use of unstable communication links among the nodes. Similar to the previous case, the limitations of this solution must be identified before trying to apply it in an urban SAR scenario.

There are also some important researches being done on collaborative wireless sensor networks, which could be extended to consider work scenarios like the one studied in this article. Bal et al. [34] and also Li et al. [35] present interesting surveys on collaborative WSN and discuss the state-of-the-art, the challenges and opportunities in this area. Based on these works we can see that most proposals assume a stable communication link among nodes, which allows performing cooperative signal and information processing. As was discussed earlier, this assumption limits the suitability of those proposals in SAR scenarios. However the reliability of the communication link could be relaxed to extend the applicability of these solutions to other work areas. In this case, the consequences of relaxing the stability of the communication link must be analyzed carefully.

Li et al. [35] also discuss the challenges of combining WSN and mobile multi-robots, and propose a layered framework that allows both swarms (i.e. a group of sensors and a group of robots) to cooperate. This proposal is very interesting, but it considers swarms composed of homogenous individuals, which does not match well with the reality of the SAR scenario. Similarly, Bellifemine et al. [36] propose SPINE, a domain-specific framework for prototyping wireless body sensor networks applications. The framework is lightweight and flexible, and it can therefore be set to address the needs of particular applications. The use of SPINE framework is shown through the development of a system for monitoring human activities, which can be used to monitor first responders during SAR activities, but do not support information sharing. Indeed C-SPINE [37] was proposed to deal with collaboration and information sharing among body sensor networks in proximity.

Similar to the WSN, opportunistic networks (oppnet) could also be considered to spread information in the search area. An oppnet is a peer-to-peer application-oriented mesh that can be used to support collaboration in various mobile collaborative situations [38,39]. These networks could contribute to improve effectiveness and efficiency of SAR activities [40]. However, most research work done on this area does not consider real-time message delivery.

Two interesting reviews of routing strategies for oppnets have been presented by Huang et al. [41] and Nguyen et al. [42]. The next section presents the main structure of a human-centric wireless sensor network, its components and the mechanisms used for information dissemination.

4. The Human-centric wireless sensor network

A Human-centric Wireless Sensor Network (HWSN) is an opportunistic network that consists of spatially distributed autonomous nodes. Oppnets utilize the communication capabilities of mobile devices to create a mesh that allows a source node to transfer data to a destination [38]. A real-time message delivery is used for that purpose. We define real-time message delivery as the process that allows the network to transfer a message from a source to a destination node, without errors and before a deadline. This process is not necessarily fast or live. The communication opportunities in these networks are intermittent; therefore, we cannot ensure that an end-to-end path will exist for the message delivery.

Three types of nodes can be part of a HWSN: *regular sensors* (e.g. GPS, weather, chemical, movement), *human-based sensors* (e.g. people that input information to the network) and *information holders* (i.e. computing devices that keep available the information delivered by the sensors). Therefore, these networks can be considered multi-sensors.

In a HWSN every node is able to send information to human-based sensors, which enhances the human-centric feature of these networks. Human-based sensors (HBS) can retrieve information from other sensors and HBS, perform information fusion and feed the network with new information pieces. These HBS can be implemented through the mobile software application used by team leaders or commanders in the field. Such application allows a user to collect context data (e.g. from sensors reporting the position of other SAR teams in the area) and produce more complex information (e.g. to determine the next search area and the route of the company). Such information could then be shared with other HBS as a way to inform them of the decisions that have been made or the relevant knowledge that could be considered to make decisions. This allows other HBS to make or adjust their local decisions to keep (at least) a minimal coordination among teams. This information sharing process gives these networks the label of "collaborative". Typically, the collaboration is always done among HBS, since the regular sensors just provide information on-demand and the information holders act as temporal repositories that help share information among HBS. Information holders are particularly useful to support information sharing among HBS that works in a different time and/or place.

In order to help conceptualize the structure of a HWSN and the role of its components, Fig. 5 shows the architecture of a generic mobile collaborative application, which allows a HBS to interact with other sensors to retrieve or disseminate shared information through the network. Since the HWSN is an overlay network, it corresponds just to the second layer of that architecture. Such a layer is in charge of capturing information from the sensors and also providing networking services to the mobile applications, e.g. messages routing, management of the network topology and users connection/disconnection. The lower layer is in charge of managing the basic networking issues; e.g. nodes identification, nodes connection/disconnection, and message passing.

Fig. 5 shows two HWSN deployed in two different search areas. One of them is being used by the Company A and the other by the Company B. Company A involves five HBS (represented with a rhomb), which correspond to five different teams; for example, the command post (black icon), three scout teams (yellow[1] icons) and a rescue team (red icon). Such an HWSN also involves three regular sensors (represented with a star); e.g. a chemical sensor, a weather sensor and a GPS. Due the HWSN try to provide real-time communication, they consider two types of information holders: *Mules* (Mu) and *Witness Units* (WU). The mules are typically computing devices installed on vehicles, which are used to interconnect the disjointed networks. In Fig. 5 these mules are represented as fire trucks (*Mu1* and *Mu2*), but they can also be implemented using ambulances or other vehicles participating in the response process.

The witness units (represented with a circle in Fig. 5) are similar to the mules, but they are mainly stationary. Their goal is to keep, in a certain area, the shared information that is relevant for any team or company passing by such an area. HBS can also use the witness units to leave shared information for other teams, although such information is not necessarily linked to the area where the unit was placed.

Finally, the upper layer (i.e. the mobile collaborative application) uses the overlay network services to receive data from regular sensors and exchange information with HBS and witness units. For example, in Fig. 5, the sensor HBS-A2, who is the leader of a rescue team, uses a mobile application that retrieves information from a seismic sensor (RS3) located at the infrastructure of a building. Such an application also allows him to inform on the stability of such a building to the command post and other response teams. Similarly, the sensor HBS-B1, who is the commander in charge of the company B, uses an application that gathers information from air diagnosis units (RS2) to determine areas of a chemical laboratory in which is safe to perform search and rescue activities. The following sections explain the main components and services considered in a HWSN.

4.1. Network nodes

As previously mentioned, the HWSN considers four types of nodes: regular sensors, human-based sensors, mules and witness units. Due HWSN are human-centric networks, they always have to include at least one HBS. The rest of the node types are optional. Next we explain each of them.

4.1.1. Regular sensor

A regular sensor is any device that responds to a physical stimulus (such as heat, light, sound, pressure or motion) and transmits a resulting impulse. In particular, transducers are special sensors that are capable of measuring a variable (e.g. temperature) and transform the measured value to a number that can be processed by a computer. Therefore, these sensors have a transducer, a microprocessor and a communication device. However, the communication capability of these nodes is not used for routing purposes as a strategy to save their energy. Typically, the message routing process is intensive in the use of the network, and therefore, energy consuming. Provided that energy is a scarce resource in most regular sensors and that they play an important role during the *golden*

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[1] For interpretation of color in Figs. 5 and 7, the reader is referred to the web version of this article.

Fig. 5. Basic architecture of a collaborative system supported by HWSN.

relief time period, we are not using them for message routing purposes. Formally, we can define a regular sensor as a function that transforms a physical value into a digital one. That function can be represented as follows:

$$\mathrm{RS}: \ X \rightarrow Y \qquad (1)$$

where X is the set of possible inputs to the sensor device, RS is the transformation implemented in the sensor and Y is the set of possible outputs. For each element in X there is only one value in Y. These sensors are deployed in the field just to measure a simple variable (e.g. temperature) and then to deliver such information on-demand to a requester (typically a HBS). The information provided by these sensors is usually simple and accurate. Examples of these sensors are the detectors of CO_2/ethane/propane, and units that measure temperature/humidity/wind speed. Of course, several types of sensors can be used depending on the activity that the team is performing, and also the type of emergency situation that is being addressed. Vital sensors are commonly used to support first aid assistance, and GPS, RF location and inertial sensors are used for tracking rescuers in the field [28,36]. Seismic/acoustic sensors are usually utilized to detect and locate live victims trapped in collapsed structures. These sensors convert vibrations created by the victim into audible/visual signals that infer and identify his/her location and health condition.

4.1.2. Human-based sensor

A human-based sensor is a special case of a RS. While a RS can only be used to provide quantitative information of a variable, the HBS can be used to provide qualitative information based on quantitative and qualitative information provided by other nodes. An HBS is able to collect such information and combine it to create new knowledge; i.e. these agents perform information fusion based on their own experiences and training. The HBS are composed of three mandatory elements: a mobile device with networking capabilities (e.g. a handheld), a mobile collaborative application (upper layer in Fig. 5) and a user of such an application. The user utilizes the application to ask for information from surrounding sensors, add information to the network and help disseminate the shared information (i.e. the HBS participate in the messages routing). For example, a collaborative application can inform the company commander on the location and number of victims trapped in a search area, which were identified by the scout teams (e.g. other HBS). If the number of victims overwhelms the rescue capability of such a company, the commander (acting as a HBS) can use the application to increase the rescue priority for the area. This information can be shared with other companies through the network, and eventually some of them could support these rescue activities.

A collaborative application used by the commander can also retrieve information from the sensors that detect the presence of chemical agents in the search area (through an RS). Based on the features of the detected agent and the wind condition (through an RS), the commander can order an evacuation, suggest an exit route and mark the area as dangerous. The information generated by the commander (i.e. the HBS) is shared through the network, and thus other SAR teams can be made aware of this information when they pass near the area.

Summarizing, the HBS does not provide highly accurate information, because it is based on a human perception. However, the information provided by HBS is usually required to make decisions during emergency response activities. An example of such information is the time available for rescuing a trapped person, before he/she dies. Formally, a HBS can be defined as a multivariable vector function, since it can process the input information and knowledge, and produce knowledge from it. An HBS is able to perform three operations: update the local knowledge, create a shareable piece of knowledge, and share a piece of knowledge with other members of the HWSN. We assume that the HBS always counts on *local knowledge* when they become part of an HWSN. Such knowledge, known as *Previous Formal Knowledge* [43], comes from past experiences, training processes and knowledge about protocols and rules in performing a certain activity. Therefore, the HBS have to keep their local knowledge updated and eventually share it with the rest of the HWSN. We call *EvolvingLK* to the function of evolving the local knowledge, using as input the information and knowledge retrieved from external sources. The *EvolvingLK* function for a particular HBS is defined as follows:

$$EvolvingLK(HBS_t): \langle K(HBS_t), I(\{HS_t\}), I(\{RS_t\}), K(HWSN_t)\rangle \rightarrow K(HBS_{t+1}) \qquad (2)$$

where $K(HBS_t)$ represents the local knowledge of the *HBS* at the time *t*, $I(\{HS_t\})$ represents the information that the person obtains through his/her senses, $I(\{RS_t\})$ is the information that he/she retrieves from regular sensors, and $K(HWSN_t)$ is the knowledge currently available in the HWSN. The *EvolvingLK* function uses such information as input and produces a new local knowledge for the node (i.e. $K(HBS_{t+1})$), which is an evolution of the previous one. This model of knowledge evolution is aligned with the proposal made by Canós et al. [44]. Eventually, after a certain knowledge evolution, the local knowledge changes to include a piece of knowledge that is relevant for other nodes of the HWSN (e.g. a change in the stability of a building in which teams are doing SAR activities). In that case, the HBS generates a message representing the knowledge that the node wants to share, which can be defined through the following function:

$$GeneratingM(HBSt): \;\; K(HBSt) \rightarrow msg \tag{3}$$

where *msg* is the piece of knowledge to be shared, which is part of the local knowledge of the HBS at the time *t*. Such a piece of information is shared using the function *SharingM*(*msg*) that is defined as follows:

$$SharingM(msg): \;\; \langle msg, Ct(msg), K(HWSNt) \rangle \rightarrow K(HWSNt+1) \tag{4}$$

where $C_t(msg)$ represents the capability that a HBS has for sharing the *msg* at the time *t*. If the sharing process is successful, the knowledge available in the HWSN increases. Therefore, a HBS can be considered a knowledge unit of a HWSN, which also has communication capabilities. The definition is not strict as it involves human behavior, thus it can be expanded to include more detailed functions.

4.1.3. Witness units

The witness units (WU) are stationary information holders that perform three simple functions: receive, store and deliver information in a HWSN. Its role is to act as a bridge among mobile nodes, e.g. HBS or mules. The information that a witness unit stores is related to its current location, and such information is delivered on-demand to nodes that are physically close to the witness device. Therefore a witness unit can be used to inform mules or SAR teams about the current situation of the search area where it is located.

Reaching this goal requires that the incident commander in charge of SAR activities in the area leaves a witness unit there and uploads on it the information that must be known by other teams when they arrive there. Thus, it is possible to avoid performing some activities twice. The witness device must rely on a positioning system (e.g. GPS), networking capabilities, data storage and 72 h of power autonomy. Similar to the RS, the witness units do not participate in the message routing to avoid consuming their energy during the *golden relief time period*, in which they play an important role disseminating the shared information of a certain area.

4.1.4. Mule

These units are also information holders that perform the same functions than the witness units. However the mules also participate in the message delivery, acting as a hub that collects information from other nodes and disseminates such according to a message delivery policy. They are used to mainly allow communication between disjoint HWSN as shown in Fig. 5. The mules participate in the messages routing not only between networks, but also inside a single mesh. Since the mule follows a temporal and predefined route, it is possible to predict the delivery time of the messages. This helps address the real-time message delivery that we can reach in a HWSN.

4.2. The communication support

The communication model supporting an HWSN considers just HBS interacting on an oppnet. This modeling decision was made because these types of nodes are the main actors of the communication process, and also as a way to understand the limits of this proposal. The introduction of mules and witness units can just improve the information availability and dissemination; therefore they were not initially considered in the network model to identify the capability of a HWSN when those information holders are not present. The mules and the witness units are special cases of HBS.

The communication model proposed in this paper considers real-time message delivery. The nodes of the oppnet participating in the message delivery provide three basic services: (1) *recording the local information*, (2) *discovering the neighbor nodes*, and (3) *exchanging one-hop messages*. Each network node acts as a sensor that records the information input by its user (e.g. a commander or the leader of a SAR team). The information shared among teams is the only one that is disseminated through the network. In order to deliver such information, a node will recognize the presence of neighbors and transmit messages to them, trying to reach the destination node.

Several factors must be considered to define a general model for an oppnet; e.g. the nodes mobility, their communication threshold and the instability of the communication. These factors and the relationships among them have a low predictability, therefore it almost impossible to combine them in a simple mathematical representation. This proposal assumes a stochastic behavior for these systems. This means that the probability that a node meets up with another is represented as a Poisson process. We call λ to the probability that two nodes meet during a certain time interval. The network behavior can be represented through λ, and the time between two successive meetings is a random variable that adheres to an exponential distribution with parameter $1/\lambda$.

Considering these simplifications we can assume that the oppnet is a Continuous Time Markov Chain (CTMC) that includes an absorbing state. The source and destination nodes respectively represent the first and the absorbing state of a CTMC. The process moves to a new state every time that a message transferred from a node to a neighbor. Therefore, the Markov chain can be represented by the number of messages copies present in the system at some time instant.

A transmission between two nodes is instantaneous and deterministic, and it occurs just if the nodes are within communication range. In these cases, it is assumed that the message transfer is completed for sure. The sojourn times are memory-less and follow an exponential law. The following differential equations indicate how to calculate, for each state, the transient probability distribution. Using the Laplace Transform (LT) we can address these differential equations.

We are considering an initial probability of $\pi(0)$ for every state of the Markov process. In Eq. (5), **Q** represents the infinitesimal matrix generator that indicates the transition rate between two consecutive states.

$$d\pi(t)/dt = \pi(t)\mathbf{Q} \tag{5}$$

The transient state probability indicates how the message is transmitted to the mesh. In order to do that, we determine the probability that the CTMC is in each state at a certain time instant. In this type of network is important to calculate the time required for a message to reach the destination node, due its delivery considers time restrictions. Such a time is equivalent to the period required by the Markov chain to reach the absorbing state, and it is usually known as the Mean Time To Absorption (MTTA). The cumulative probability for a state can be calculated as follows:

$$\mathbf{L}(t) = \int_0^t \pi(u)du \tag{6}$$

Eq. (6) can be expressed through a set of differential equations:

$$\begin{aligned} &\frac{d\mathbf{L}(t)}{dt} = \mathbf{L}(t)\mathbf{Q} + \pi(0) \\ &\text{with } \mathbf{L}(0) = 0 \end{aligned} \tag{7}$$

The limit lim $m_{t\to\infty}\mathbf{L}(t)$ establishes the time required to reach the absorbing state (i.e. the destination node). These equations compute only non-absorbing states (the absorbing state was not considered in the **Q** matrix). Applying the limit on both sides of (7), the following linear equations are obtained:

$$\mathbf{L}(\infty)\mathbf{Q} = -\pi(0) \tag{8}$$

Based on Eq. (8) we can obtain the Mean Time To Absorption as follows:

$$\text{MTTA} = \sum_{i=1}^{N} Li(\infty) \tag{9}$$

In an oppnet it is important to determine the expected number of message copies that are present in a certain time instant, because the resource consumption during the dissemination depends on it. Using Eq. (5) we can calculate this number, at time *t*, as indicated in (10).

$$m(t) = \sum_{i=1}^{N} i\pi_i(t) \tag{10}$$

The communication model presented for an opportunistic network is general, and it was not conceived to be implemented over a certain network or transport protocol. Since a HWSN is an overlay network that needs direct interaction with the mobile application used by the HBS, we conceive their implementation at the application layer. An example of this type of implementation is the HLMP API [26] that provides an implementation of the HLMP routing protocol [45] at the application layer. Such an infrastructure uses UDP/IP to discover peers and manage the network topology, and TCP/IP to share information among the network nodes. Implementations over popular protocols usually contribute to use devices with regular technology, which helps reduce their cost. As mentioned earlier, this is a relevant aspect in this proposal.

This is well-known that oppnets and MANETs (Mobile Ad hoc Network) implemented using WiFi are not reliable. However, it is also well-known that they can be used successfully to share information in mobile work scenarios (e.g. in SAR activities) when some communication requirements are addressed properly. Two key requirements are: (1) to take into account the communication threshold and bandwidth of these networks, and (2) to implement a network topology management service able to react quickly to topology changes. Thus, when two nodes are in contact, they will be able to maximize the time period for message exchange.

4.3. Considerations on the information sharing process

As described in Section 4.1, each HBS has to manage his private information (retrieved from regular sensors) and shared information (retrieved from the HWSN). Therefore, every HBS must implement a private and a public space. The private space is visible only to the local user of such a unit, and the public space is visible for all members of an HWSN. The information to be shared with other nodes must be kept in the public space.

The sharing process of such information is performed on-demand by HBS nodes. Depending on how well this process is done, the availability of the supporting information in the field can increase or decrease. This is particularly relevant when the HWSN use a communication infrastructure that considers unreliable links and a limited bandwidth.

Typically the information sharing process must be as simple as possible, because the first responders work under pressure during SAR activities and they have no time to spend in tasks that are not directly relate to find or rescue people. The information that is shared through the network must be useful, interoperable, and as lightweight as possible. The first attribute ensures the relevance of such information, the second one ensures its understandability by other users or software systems, and the third one determines its transportability through the network. Other relevant attributes of the information, such as accuracy or trustworthiness depend on the behavior of the people sharing knowledge through the mesh.

In order to try maximizing the usefulness of the information, it is recommended that every piece of shared knowledge (i.e. a shared information record) has a timestamp and a georeference. Such context data can then be used to determine the information that is potentially outdated or the physical place that is referenced by a record (e.g. the number of victims still trapped in a building).

The internal structure of the shared information can be known (e.g. a descriptor or a record) or unknown (e.g. a picture or a map). Information with a known internal representation can be shared among nodes using two mechanisms: file transfer or data synchronization. The first one involves the transference of the file and the overwriting of any pervious resource with the same name in the target unit. The second one involves a data reconciliation process, where two files are mixed in a single one that keeps the same structure than the source files. It can be considered an information fusion process, where the data kept in the resulting file is determined by a resolutor that establishes the rules to perform such synchronization process. Neyem et al. [46] describe a mechanism to perform data synchronization in a simple way, when the files structure is known. The advantages to perform data synchronization instead of file transfer are mainly two: the resulting information can be kept in a single file and also the information to be transferred through the network is just the minimal required for the files fusion. It is recommended that shared information having a known internal structure be represented using a standard data format, like XML. Such a format has also the advantage that is lightweight, and ease to integrate with other XML files, which minimizes the messages transportation through the network [46] and therefore increases its availability.

In the case of shared information with an unknown internal structure (e.g. a picture or a sketch), the most usual method to share it is the file transfer. These files could be serialized and separated in several information chunks to ease its transfer to the destination node. However such a decision should be made by the software developers in charge of designing the mobile application that handles this public information.

A simple strategy to share this heavyweight information was proposed by Monares et al. [7]. That strategy involves the management of information in layers that are shown on-demand over precharged maps. Thus, just the layers of information (that are usually lightweight) are shared among the network nodes. The next section describes two strategies for disseminating the shared information among HBS participating in a HWSN.

5. Message routing in HWSN

This section shows how to perform the information dissemination process in a HWSN using the *epidemic routing* and *spray and wait* routing algorithms. This follows two main goals: (1) to illustrate that several algorithms can be used to route messages in a HWSN and (2) to show that the benefits of using a HWSN do not strongly depend on the chosen algorithm. In this section we also compare the information flow considering these algorithms. The epidemic routing strategy is inspired in the way in which a biological virus is disseminated; i.e. the strategy assumes that a node holding a message copy will transfer it to its neighbor nodes during a single phase. Contrarily, the spray and wait algorithm uses two phases to deliver the message. During the spray phase the source node delivers the message up to R neighbors. Then, in the waiting phase, the source node does not perform any action, but the $(R + 1)$ nodes holding the message copies can pass them to their neighbors, trying to reach the destination one. Next two sections indicate how to perform this information dissemination in a HWSN, depending on the routing strategy. Section 5.3 compares the performance of both algorithms, and Section 5.4 determines the worst acceptable case for information delivery using these routing strategies.

5.1. Epidemic routing algorithm

Epidemic routing is a resource demanding algorithm that has a high dissemination speed. The use of this routing strategy could be appropriate when the messages should be delivered under time restrictions. The transient probability function in these networks can be calculated using the Inverse Laplace Transform (LT^{-1}). Therefore the Mean Time To Arrival for this routing strategy can be determined through the following equation:

$$\mathrm{MTTA} = \left(\frac{1}{N\lambda}\right)\sum_{i=1}^{N}\frac{1}{i} \tag{11}$$

5.2. Spray and wait algorithm

The CTMC model for spray and wait assumes the same network behavior than for epidemic. However, in this case only a small number of nodes ***R*** hold the message copy. Those nodes can be HBS, witness units or mules. In this case, the transient probability function of the CTMC can also be calculated using the Laplace Transform, as indicated in (12):

$$\mathrm{MTTA} = \left(\frac{1}{\lambda}\right)\left[\left(\frac{1}{N}\right) + \sum_{i=2}^{R}\frac{(N-1)!}{((N-i)!N^{i})} + \sum_{i=R+1}^{N}\frac{(N-i+R-1)!}{((N-i)!N^{R})}\right] \tag{12}$$

Eq. (10) allows us to determine the average number of message copies in the mesh just before that the message is delivered to the destination node. However, in this case the equation should be modified to consider not only the number of message copies but also the movement of the source node:

$$m(t) = \sum_{i=1}^{R} i\pi_i(t) + \sum_{i=1}^{R} R\pi_i(t) \tag{13}$$

5.3. Epidemic vs. spray and wait

This section presents an example of an oppnet composed of six relays and one destination node. In that scenario, the performance of epidemic and spray and wait was compared in terms of the MTTA and $m(t)$. In order to calculate the value of these indicators, we have to determine the infinitesimal matrix generator $\mathbf{Q}$ (as shown in [16]) for both routing strategies. We are considering $\lambda = 1$, as a way to ease the presentation.

Eqs. (11) and (12) allow us to determine the MTTA for these routing strategies. For epidemic the $\mathrm{MTTA_e} = 0.41$ and the $m(\mathrm{MTTA_e}) = 4.44$. For spray and wait the $\mathrm{MTTA_{s\&w}} = 0.49$ and the $m(\mathrm{MTTA_{s\&w}}) = 2.74$. These results show that the message dissemination is faster when an epidemic strategy is used; however in spray and wait the dissemination process demands less network resources than in epidemic. In activities like urban SAR, using few resources for message dissemination is mandatory, due it helps reduce the energy consumption of the nodes and increase their autonomy.

5.4. The worst case behavior in oppnets

We have already shown that the number and mobility of the network nodes determine the average performance of the message delivery process. For real-time applications (like those supporting SAR activities) the routing strategy has to keep the message delay within bounds. The maximum acceptable delay is known as the Worst Case Time to Absorption (WCTA). The use of the WCTA allows us to transform the network behavior from stochastic to deterministic. However, the communication process keeps moving from one state to the next one (until it reaches the destination node), even if a CTMC is not used.

A direct message transfer is done just when the source and destination nodes are neighbors. The time required by the source node to reach the destination can be calculated if the first one has a known mobility pattern and it also knows the location of the destination. In that case, the WCTA can be calculated using the distance between the source and destination nodes, and the average message dissemination speed (i.e. the Velocity Make Good – *VMG*).

$$\mathrm{WCTA} = \frac{distance}{VMG} \tag{14}$$

The worst case situation in epidemic routing is reached when the nodes are deployed in a line, and therefore the destination node will be the last one in receiving the message. Eq. (15) indicates how to calculate the WCTA in a network with a linear topology:

$$\mathrm{WCTA} = \sum_{i=1}^{N}\frac{distance_{i,i+1}}{VMG_i} \tag{15}$$

In spray and wait, the WCTA involves a topology similar to the previous one, where the last interim node is the only one able to pass the message to the destination node. Therefore, the WCTA can be calculated as shown in (16):

$$\mathrm{WCTA} = \sum_{i=1}^{N}\frac{distance_{1,i}}{VMG_{1,i}} + \frac{distance_{R,destiny}}{VMG_{R,destiny}} \tag{16}$$

5.5. Introducing information holders

As mentioned before, the HWSN consider the eventual presence of two additional types of nodes that act as information holders, i.e. the mules and the witness units. However, just the mules participate in the messages routing. Let us consider the previous network model (i.e. composed by just HBS nodes) but now including mules, which have a particular mobility pattern that usually allows the information exchange among sub-networks that are isolated. If these mules have a known path and period, then we can determine the WCTA. The WCTA will be reached if the message to be disseminated is created by a node immediately after the *mule* has loss the contact with it. Therefore, such a node should wait for a T_p time (i.e. the mules period) to deliver the message to the next mule. Then, the mule receiving the message will require a T_f time to deliver it to the destination node.

$$\mathrm{WCTA} = T_p + T_f \tag{17}$$

In order to calculate an end-to-end WCTA among different sub-networks connected through mules, we can combine the Eqs. (14)–(17). The behavior of the network will depend on the throughput, the number of nodes and the nodes meeting rate (λ). In the case of a SAR company, the meeting rate is usually high due its members (i.e. the network nodes) work in quite small areas. Determining an accurate value for λ is almost impossible, because it depends on many interdependent variables that describe the disaster situation. However, we can ensure that the message delay will decrease if we increase the number of network nodes.

Trying to address this situation, we can use the mules to help increase the nodes' meeting ratio and the throughput of a HWSN. A similar effect can be obtained by introducing witness units. However, the improvement in that situation is difficult to quantify, since the data exchange between a witness unit and any other node is done on-demand. Therefore it would depend on the behavior of the requesting node, which in the case of human beings, is almost unpredictable. However it is clear that the presence of a witness unit is, in the worst case scenario, harmless to the HWSN.

In the case of mules, the best scenario to help increase the HWSN transfer ratio is when all mules in the field are available to support message exchanges. However, delivering real-time messages requires calculating the WCTA to keep the message delay within bounds. The message delivery should be predictable, even in the worst case scenario. Although we cannot guarantee a throughput because the network behavior adheres to a stochastic model, we can incorporate periodic mules to try guaranteeing that the message delay will be under control.

6. Simulated SAR process

In order to show the potential benefits of using HWSN to increase the information availability during SAR activities, we will analyze the information availability in a simulated SAR scenario. Such a scenario was created according to a real situation that happened in the city of Concepcion (Chile) after the earthquake struck on February 27, 2010. The firefighter captain in charge of SAR activities in that area helped us to create and validate the simulated scenario. This person is also in charge of the SAR training program in Chile, and has 25 years of experience in urban search and rescue. Although his opinion does not represent a general validation, it provides some insight about the possible impact of this proposal. Next sections present the simulation settings and also the obtained results.

6.1. Simulation settings

The simulated SAR process adheres to the protocol described in Section 2. Therefore, the first step is to determine the search area. The locations and limits of such areas depend on several variables, such as the commander's experience, the number of resources available for SAR activities, and the work done (or being done) by other companies in the neighborhood. In other words, the physical area to be scouted is dynamically divided by the commanders using their own criteria. Therefore it is common to see overlapped search areas and also areas that have not been covered by the SAR companies. Fig. 6 shows a quite usual scenario, where a physical area has been divided in several search areas (in this case, from A1 to A8).

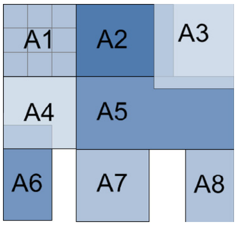

Fig. 6. Distribution of search areas in the simulated SAR process.

In this simulation we analyze the work of the company in charge of the operations in the search area "A1" (see Fig. 7). That company involves ten teams: a command post (represented with a black rhomb), six scout teams (yellow rhombs) and three rescue teams (red rhombs).

Every team leader and the incident commander is a HBS, i.e. a mandatory network node. No mules and witness units were included in the search area, because they are not mandatory nodes. Moreover the inclusion of such information holders only could impact positively on the communication capability and information availability in that area.

This SAR process considered scout teams reviewing the area and identifying the rescue places, which are indicated with a rectangle in Fig. 7. Periodically a member of each team informs to the incident commander about the search results. When trapped victims are identified, it is immediately informed to the commander, who assigns one or more rescue teams to such a rescue place.

This SAR process was analyzed considering two alternatives for interaction support in the field: (1) when a regular approach is used (i.e. the process is supported only by VHF/UHF radio systems), and (2) when HWSN are added as an extra support for that activity. Several qualitative and quantitative variables were observed in both scenarios to understand the potential impact of using HWSN. These variables were selected after a preliminary analysis done with the firefighters captain, in which we try to identify the variables that affect the performance of the SAR process and that can be impacted positively with the use of HWSN.

In the first simulation scenario, the values of the observed variables were determined by the firefighters captain supporting this simulation. In the second case, the values of the variables were established using two different sources, depending on the type of variable to be considered. The quantitative variables were set computing some of the equations presented in Section 5, using the appropriate parameters. The qualitative variables were determined by the firefighters captain, using the simulation results as supporting information. Next we present the quantitative variables that were observed in the simulation process.

6.1.1. Duration of each information reporting process

As explained before, a member of each team must periodically report the results of each mission to the command post. The average duration of that process can be determined based on the Mean Time To Absorption (MTTA) of a message, and the maximum duration can be determined based on the Worst Case Time to Absorption (WCTA).

6.1.2. Time required to retrieve operative information

This variable indicates the time required by a company to retrieve the operative information that is need to conduct SAR activities in a certain area; for example, the status and limits of the search area, the pending rescue places and the presence of others companies working in the area. This time will depend on how direct is the access to such information. Due this type of information is required almost permanently by team leaders and the incident commander, this access time affect directly the performance of every company.

6.1.3. Average number of message copies in the network

This variable indicates the number of message copies that are available in the network, just before that the message is delivered to the destination node. Clearly the availability of the supporting information in the field tends to increase with the number of message copies.

6.1.4. Number of synchronization nodes

This variable indicates how many nodes in the network are available to exchange information with a certain node. A more

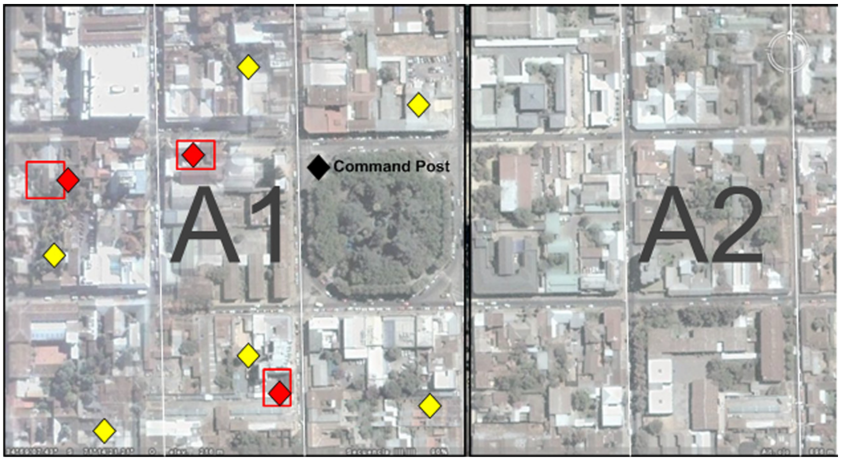

Fig. 7. Structure of the search area "A1".

important number of synchronization nodes increases the feasibility of the reporting process and reduces its duration.

The qualitative variables observed in both simulation scenarios were the following:

> *Number of instances to disseminate the shared information*. The information dissemination is a process that can be attended, partially attended or unattended, depending on the level of direct participation of the user in that process. The more automatic the dissemination process is, the more important the number of instances to propagate the shared information will be. A more important number of dissemination instances increases the availability of the shared information in the field.
> *Information fusion effort*. This variable indicates the effort required by a HBS (in this case, an incident commander or a team leader) to fusion the new data with the legacy information. This effort affects the generation of new knowledge that supports the decision making process.

We have considered that the simulated reporting process involves: (1) the transfer of a XML file (100 Kbytes) containing the shared information from a scout or rescue team, (2) an oppnet with a throughput of 100 KBytes/s (which is a regular throughput for a MANET implemented using Wi-Fi [26]), and (3) a data synchronization time period of eighty seconds, which is the time required to synchronize two XML files (100 Kbytes each file) using a tool like the *μXML Synchronizer* [46].

The average walking speed during the reporting process was set to 1.5 m/s and the absorbing point was always the command post. The meeting rate of the nodes (1/λ) was determined based on a firefighters movement simulation performed by the authors using an adaptation of the Gauss-Markov Model [47]. Although this model does not describers exactly what is happening in the field in every time instant, it is representative enough to consider the simulated movement as acceptable for this scenario. Next section presents the obtained results and discusses the limitations of this simulation process.

6.2. Obtained results

Table 1 shows the values of the quantitative variables for both simulation scenarios, i.e. when the communication support used for information delivery is a VHF/UHF radio system and when HWSN are used as an additional support for such an activity. Moreover, two alternative implementations of a HWSN were considered in this simulation. The first one used an *epidemic* strategy to disseminate the information, and the second one used *spread and wait* routing (spreading up to three nodes in the same round).

As mentioned before, the average duration of the reporting process for the first scenario was estimated by the firefighters captain. The regular protocol for this process considers that the team member goes to the command post, waits for the incident commander availability, and reports the activity results. In case of using a HWSN as an extra support, the team member walks toward the command post (following the regular protocol), but the reporting process is done immediately after a network path is created between these nodes. Therefore, this reporting process can be done at distance if both nodes (i.e. the team member and the incident commander) are inside the communication threshold. Considering that the HWSN has routing capability, in most cases the team members could inform to the command post without moving from the working place. This dramatically reduces the time spent today by these workers and automatically generates a picture of the area, which can be monitored online by the commander. It also leaves the commander more time to make decisions.

In this case, the MTTA for a HWSN that uses an epidemic strategy (HWSN_{e}) is calculated using Eq. (11), and when the network uses spray and wait ($\mathrm{HWSN}_{s\&w}$) the MTTA is calculated using Eq. (12). The average duration of the information reporting process also considers the time period in which the team member walks towards the command post (before to get a communication link with it), and also the eighty seconds required to perform the data synchronization between the nodes (i.e. to perform the reporting process using the XML files).

Retrieving operative information from the command post is equivalent to reporting information, therefore the values of the variables are the same in both cases. Although these values are not accurate, they are representative enough to identify that there is an order of magnitude of improvement when a HWSN is used to support the information reporting and retrieving process. These values would improve if we add mules to the SAR process.

At the absorption time, the average number of message copies is usually equal to 1, due only the team reporting the information has the message before deliver it to the command post. When a HWSN is used, this variable (i.e. the *m(MTTA)*) can be calculated using Eq. (13). In this case the results indicate that the shared information of a team is spread to other nodes before reporting it to the command post, which is an expected result. Thus, the use of HWSN increases the availability of this information to the teams working in the area.

The number of synchronization nodes in a regular scenario is only one (the command post). However, when a HWSN is used,

Table 1
Quantitative results of the simulation process.

Variable	VHF/UHF (Regular Scenario)	HWSN (Epidemic)	HWSN (Spread and Wait)
Average duration of each information reporting process (based on the MTTA)	20 min	175 s	192 s
Maximum duration of each information reporting process (based on the WCTA)	30 min	247 s	303 s
Average time required to retrieve operative information (based on the MTTA)	20 min	175 s	192 s
Maximum duration of the operative information retrieving process (based on the WCTA)	30 min	247 s	303 s
Average number of message copies (m(MTTA))	1 copy	5.7 copies	3.3 copies
Number of synchronization nodes	1 node	9 nodes	9 nodes

every node is a potential synchronization point. This allows the nodes to use several strategies to report their activity results. Moreover, this helps increase not only the information availability in that area, but also the opportunities for information dissemination. These capabilities also increase considerably if we include witness units or mules in the area.

Clearly each routing strategy has benefits and limitations that affect the time involved in the information dissemination and the availability of such information. However, these differences are not relevant compared to the decision of using (or not) HWSN as an extra support for firefighters in the field.

Table 2 shows the qualitative variables observed in this simulation process. In this case, we did not consider the routing strategies to determine the value of each variable when using HWSN, because the difference between both strategies are not significant, and also because these values were established based on the captain opinion.

In the regular process, the information dissemination requires the active participation of the people reporting and receiving the information. This process is performed in a manual way, therefore it is usually time consuming and error-prone. Moreover, the process requires that the participating nodes should be physically close and available at the same time period, which reduces considerably the number of instances to perform information dissemination. Contrarily, when HWSN are used, the information dissemination process is unattended. Therefore every time that two nodes are in the same communication threshold, a new opportunity for information dissemination is created. Due the HWSN allow the automatic information dissemination, this process is not time consuming or error-prone.

Concerning the information fusion (performed after the dissemination) in the regular scenario, such a process is also done in a manual way. As previously mentioned, this process is also time consuming and error-prone. Contrarily, in a HWSN-based scenario the mobile applications used by the HBS can perform an automatic data synchronization, that eases the information fusion and reduces the number of errors. As mentioned in Section 4.3, this data synchronization requires knowing the internal structure of the files to be merged.

The simulation presented in this section does not intend to reproduce the dynamic of the SAR process. Instead of that we show how the information dissemination services, which are required almost permanently by team leaders and the incident commander, can be improved using a HWSN as an extra communication support. Although the results of the observed variables can change from one scenario to another, the improvement in terms of information availability and dissemination speed will be important almost in any case. Determining accurately the magnitude of this improvement will require the development of a simulation tool that considers the three mandatory models proposed by Bradler et al. [48]: the work scenario, the nodes movement and the communication network. This challenge will be addressed as part of the future work.

7. Conclusions and future work

The typical limitations to count on useful and on time information in the field represent still open problems. Most proposals trying to deal with this issue address a part of this problem or require specialized and expensive equipment. For that reason, the most well-known and used method of sharing information in the field involves physical marks that first responders make on the infrastructure.

To address this challenge this article introduces the concept of human-based wireless sensor network, which can be seen as opportunistic networks that intend to provide real-time communication support among the nodes. Such nodes are mainly human-based sensors, but the network also considers the inclusion of regular sensors, mules and witness units. This network is multi-sensor and collaborative, and the HBS are the nodes mainly responsible for information dissemination and fusion.

The article formalizes the communication model of a HWSN and also the types of nodes participating in this network. The epidemic and spray and wait routing strategies have been used to show how to implement a HWSN for information gathering and dissemination in the field. This also helps to show that the advantages of using a HWSN do not depends on the routing strategy used to deliver the information. The results indicate that the epidemic dissemination is faster than the strategy followed by spray and wait. However, both algorithms are suitable to help increase the information flow in a disaster area. The network throughput in the field can be increased if mules are added to the system.

In order to deal with real-time message delivery in a HWSN, an equation to calculate the *Worst Case Time to Absorption* has been proposed. This variable establishes the maximum delay that can be found in a message delivery. This article also proposes an equation to determine the *Mean Time To Absorption*. This indicator represents the average time involved in a message delivery. These indicators allow us to understand the way in which the messages flow through the network. Understanding the network behavior allow us to determine if mules are required to interconnect sub-networks (i.e. teams) in the field or increase the network throughput. Usually these actions impact positively the information availability in the field and the efficiency of the SAR activities.

Table 2
Qualitative results of the simulation process.

Variable	Regular process	Using HWSN
Number of instances to disseminate the shared information	*Few* (this is an attended process)	*Many* (this is an unattended process)
Information fusion effort	*High* (manual process)	*Low* (automatic process)

A simulated scenario was analyzed with the support of a fire company captain that is an expert in urban search and rescue. Two alternatives were considered and compared: the SAR process supported by the regular tools and also by HWSN. The results indicate that the information reporting and gathering process, using HWSN, requires a minimal effort for the involved people, and the flow of information among human-based sensors (i.e. commanders and team leaders) is considerably superior. It produces an improvement in the information availability and quality in the field that eases most activities involved in the SAR protocol. Using HWSN most activities can be done with certainty and using a direct or indirect access to the components of a search area. It should positively impact the effectiveness and efficiency of the SAR process. Quantifying such impact is part of the next steps of this initiative.

Since the HWSN model is computable, it can be used to support the design of *emergency preparedness* and *response* plans [49]. In this later phase, the model can contribute to diagnose the communication availability and flow in the field, and also to identify areas where mules are required.

The next steps of this initiative consider evaluating the proposed model during firefighters training activities. The obtained results allow us to determine real strengths and weaknesses of this communication model.

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