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Medical emergency alarm dissemination in urban environments

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ABSTRACT

During medical emergencies, the ability to communicate the state and position of injured individuals is essential. In critical situations or crowd aggregations, this may result difficult or even impossible due to the inaccuracy of verbal communication, the lack of precise localization for the medical events, and/or the failure/congestion of infrastructure-based communication networks. In such a scenario, a temporary (ad hoc) wireless network for disseminating medical alarms to the closest hospital, or medical field personnel, can be usefully employed to overcome the mentioned limitations. This is particularly true if the ad hoc network relies on the mobile phones that people normally carry, since they are automatically distributed where the communication needs are. Nevertheless, the feasibility and possible implications of such a network for medical alarm dissemination need to be analysed.

To this aim, this paper presents a study on the feasibility of medical alarm dissemination through mobile phones in an urban environment, based on realistic people mobility. The results showed the dependence between the medical alarm delivery rates and both people and hospitals density. With reference to the considered urban scenario, the time needed to delivery medical alarms to the neighbour hospital with high reliability is in the order of minutes, thus revealing the practicability of the reported network for medical alarm dissemination.

1. Introduction

The expansion of information and communication technologies led to new models for healthcare management and delivery (Boric-Lubecke and Lubecke, 2002; Lin, 1999; Pattichis et al., 2002). The potential to reduce the distance between patient and health care providers, together with the ability to obtain information to better manage individual wellness, could improve the efficiency and quality of care (Dishman, 2004; Fratini et al., 2013; Lin, 1999; Ruffo et al., 2010; Varshney and Vetter, 2000). In this framework, the emerging mobile wireless technologies have been pervasively integrated in health care systems (Stanford, 2002; Varshney, 2003), improving the effectiveness of medical professionals in:

- Routinely activities: concerning patient’s condition and therapy monitoring (Pasquariello et al.,2010; Fratini et al, 2014).
- Communications: allowing health care workers to be always reached for consultation.
- Information access: to examine medical records and general patient data anywhere and anytime (Ammenwerth et al., 2000; Cesarelli et al., 2011).

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Mobile devices such as smart phones or Personal Digital Assistants (PDAs) reached a great diffusion in the last decade (ABI, 2009) and their number is increasing (Coda, 2010). The hardware characteristics of such devices allow direct wireless connection with medical equipments, wearable monitoring systems (Bifulco et al., 2011) and other similar architectures (Anliker et al., 2004; Dabiri et al., 2009; Wac et al., 2009). Moreover, wireless networking solutions, such as wireless LANs, ad hoc wireless networks and GSM/3G infrastructure oriented networks have been tested and proven to be reliable in emergency situations or simulated critical events (Martí et al., 2009; Monares et al., 2011; Scott et al., 2002).

Numerous are the examples of mobile health research in the field of medical emergency. Consistent challenges were found for rapid emergency response (Blackwell and Kaufman, 2002; Pons and Markovchick, 2002) and information management (Chan et al., 2004; Monares et al., 2011): "*applications that combine timely, clinical information with accurate geographic localization may result particularly useful*" (Chan et al., 2004).

Different strategies have been proposed to manage a medical emergency during critical events or disasters. Some examples are based on 3G networks or radio communications: in (Kwan and Lee, 2005), the authors explored the use of Universal Mobile Telecommunication System (UMTS) in connecting building sensors in a three dimensional real-time analysis of urban scenario to help rescuers in coordinating rescue operations. In (Plischke et al., 1999), the authors analysed the potential of telemedical support in pre-hospital management of emergencies and transmission of data via digital radio network to overcome obsolescence of paper based documentation and enhance medical treatment workflow. Operation through network infrastructures was also proposed in (Dai et al., 2011). The authors argue that the first and most effective intervention can be offered by the people surrounding the disaster area so that a first-aid instruction given by medical experts, thorough the use of 3G mobile network can minimize casualties. An interesting solution was similarly suggested in (Martí et al., 2009). The study proposed a mobile triage system, based on patient tagging at the site of emergency, operating through a mesh network formed by medical emergency personnel handheld devices and able to work in absence of network infrastructure.

Although the different solutions proposed represent valuable approaches, the risk that during critical events, disasters or mass gathering medical emergencies, they do not work properly, due to failures or congestion of traditional infrastructure-based networks (i.e., GSM/3G cellular networks), is high (Maningas et al., 1997).

In case of mobile triage scheme moreover, it is worth mentioning that such a system would be effective only at the time when field medical personnel arrive on site after the emergency medical systems (EMS) intervention request.

In case of difficulty of medical alarms transmission, an alternative message dissemination system may result precious, especially when the need to request a rescue action or to inform approaching rescuers on the state and the site of the injured individuals is vital (e.g., in mass emergency).

Mobile phones-enabled ad hoc networks represent a feasible way of dissemination of alarm messages in emergency events. Nevertheless, the usefulness of adopting such a solution to the medical field has not been evaluated yet and the potential implications and limitations of this approach should be assessed.

With this study, we aim at analysing the feasibility of medical alarm dissemination through ad hoc wireless networks formed by mobile phones. In particular, we intend to present the expected delivery times for alarm dissemination in an urban environment based on realistic people mobility.

2. Methodology

This paper presents an evaluation of the feasibility of a partially connected ad hoc network established by mobile phones carried by human beings for disseminating medical emergency information in urban environments. To obtain realistic medical emergency information dissemination, we model the human mobility according to the results of an experiment involving one million mobile phone users of a US telecom operator in the Boston Metropolitan area, whose positions have been anonymously traced during the month of July 2009 (Cacciapuoti et al., 2013).

More specifically, a set of 200 millions of anonymous location measurements have been considered. Such a dataset covers a region spread over 8 counties in East Massachusetts (Middlesex, Suffolk, Essex, Worcester, Norfolk, Bristol, Plymouth, Barnstable) with an approximate population of 5.5 million people, and it involves one million mobile phones (corresponding to a share of 20% of the population approximately), traced for roughly a month. The location measurements have been recorded each time a device connected to the cellular network, and each location measurement represents the position, i.e., the latitude and longitude, of a certain device estimated through triangulation.

As in (Cacciapuoti et al., 2013), we select as event representative of a possible medical emergency the Boston Independence Day Celebration on July 4th 2009[1]. During this day people usually congregate around the Charles river (the area depicted in Fig. 1) to attend the concert and watch fireworks organized by the city administration.

The choice of the Independence Day was not arbitrary, since it allows us to evaluate the feasibility of a partially connected ad hoc network for disseminating medical emergency information during a crowd gathering event when:

- Emergency events likely happen.
- The knowledge of the accurate location of the emergency event has high relevance concerning the severity of the possible injuries or the crowding of the access paths.

[1] http://www.july4th.org.

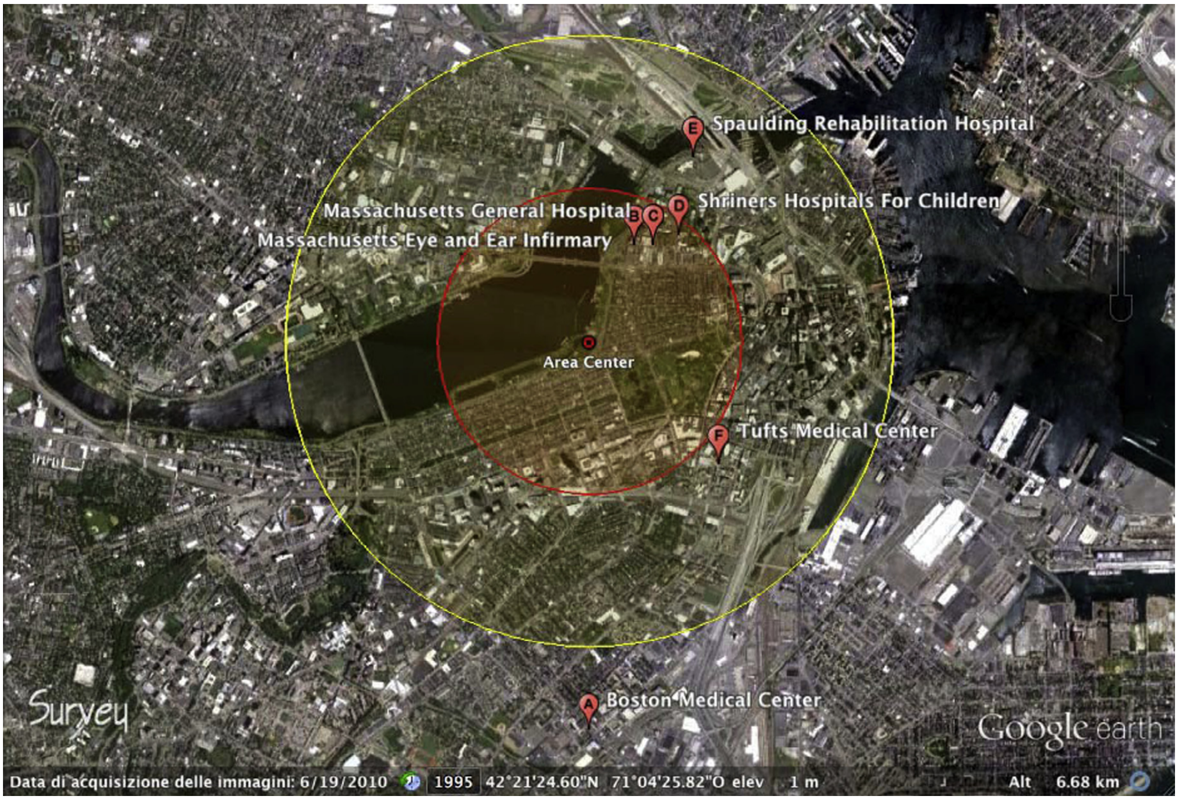

Fig. 1. Boston metropolitan area. Red and yellow circles represent the areas around the location of the medical emergency event with 1 and 2 km radius, respectively. The red bins represent the locations of hospitals equipped with emergency rooms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The data set has been subsequently processed in order to derive a realistic mobility model for people attending to the Boston Independence Day Celebration. Hence, among the 1 million mobile phones traced for roughly a month, we select the users who, during July 4th, 2009 between 01:00 and 23:59 pm, (i) made at least one connection to the cellular network every hour; (ii) were located in that area under analysis, namely the Boston City area, during at least 80% of the calls. The number of selected users was 703.

2.1. Inferring transmission opportunities from human mobility

In assessing the reliability of a network established by the mobile devices for disseminating information on a medical event, we suppose that cellular infrastructures are not working. This is particularly reasonable during disasters or mass emergency events in which critical infrastructures, such as transportation and communication, may be congested or damaged. As a consequence, Wi-Fi ad hoc communications represent the only feasible solution to exchange data.

The assumption of Wi-Fi enabled devices is justified by market research analyses, which estimate 144 million Wi-Fi enabled mobile phones worldwide shipped in 2009 (ABI, 2009) and predict that the Wi-Fi enabled phone penetration would quadruple by 2015, reaching the 66% of all mobile phone shipments (Coda, 2010).

Nevertheless, medical alarms differ from other data. A medical alarm can be effective if it is delivered in a short time, which depends on the type and severity of the subject injury.

Therefore, the time of alarm delivery and the distribution of hospitals, ambulances and medical personnel in the surrounding area are of great importance in the expectances of positive resolution of a medical emergency.

To infer the opportunities for a medical alarm packet transmission from the human mobility patterns, we imported the 703 mobile phone traces in a network simulator, Network Simulator 2 (ns-2) (Fall and Varadhan, 2011). The adoption of ns-2 allowed us to simulate the effects of all the involved layers (physical, data link and networking) on the medical alarm dissemination process.

To take into account the Wi-Fi technology properties, we assumed a transmission range shorter than 50 m, as shown in Fig. 2, where the probability of successful reception of a medical alarm message between two mobile phones is given as a function of the distance. The adopted transmission range allows us to model the effective transmission ranges of the different Wi-Fi standards (Caleffi et al., 2008; Caleffi and Paura, 2011). According to this, in a certain time slot two users experience a transmission

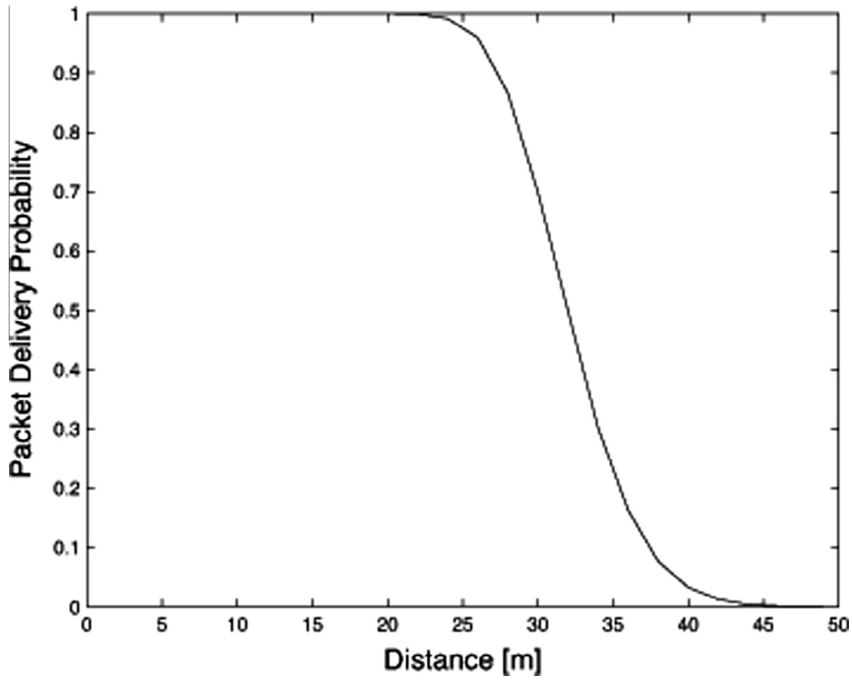

Fig. 2. Packet delivery probability. Probability of successful reception of a medical alarm message as function of the distance between two mobile phones.

opportunity with a probability whose value depends on their mutual distance. We note that the location measurements could be affected by a localization error greater than the adopted transmission range. However, since the localization error of the measurements can be assumed independent and identically distributed with zero mean, no biases are introduced in the statistics of inferred contact events, as demonstrated in previous research (Cacciapuoti et al., 2012).

2.2. Disseminating medical emergency information

As previously detailed, we consider a scenario in which a medical emergency happened in an urban environment (Hatch Shell, Boston, MA) and a medical alarm message must be broadcasted to the closest hospital or ambulance.

In the considered scenario, either the person involved in the medical emergency or the closest persons attending the event can broadcast an alarm message through an application installed in their mobile phones. The alarm message is intended to contain useful information for the medical team, such as:

- The absolute location obtained through a GPS-enabled mobile phone or the relative location obtained through estimation techniques, to easily reach the patient site.
- A brief vocal message recorded by the person who activates the alarm message to evaluate the seriousness of the medical emergency or,
- An injury severity codification string (red/yellow) as usually adopted in hospital medical emergency classification (Martí et al., 2009).

For the medical emergency dissemination, we assume that other mobile phones present in the surrounding of the emergency event location cooperate in spreading the alarm by adopting a simple store-and-broadcast protocol (Cacciapuoti et al., 2009, 2010).

Once a mobile phone receives an alarm message from one of the neighbouring phones, it keeps broadcasting the message every τ seconds[2]. Moreover, we assume such a protocol to be transparent to users to avoid voluntariness in the alarm transmission and set to the lowest possible time-interval for broadcasting the alarm.

To compute the probability of a medical alarm message being correctly received by the hospital or the ambulance, we adopted the procedure described in the follow. We first compute the alarm delivery ratio $r(t;\, d)$:

$$r(t,d) = \frac{|A(t,d)|}{|N(t,d)|}, \tag{1}$$

[2] In our experiment $\tau = 1$ sec since such an interval time is commonly used in ad hoc routing protocols for state information or route discovery signaling.

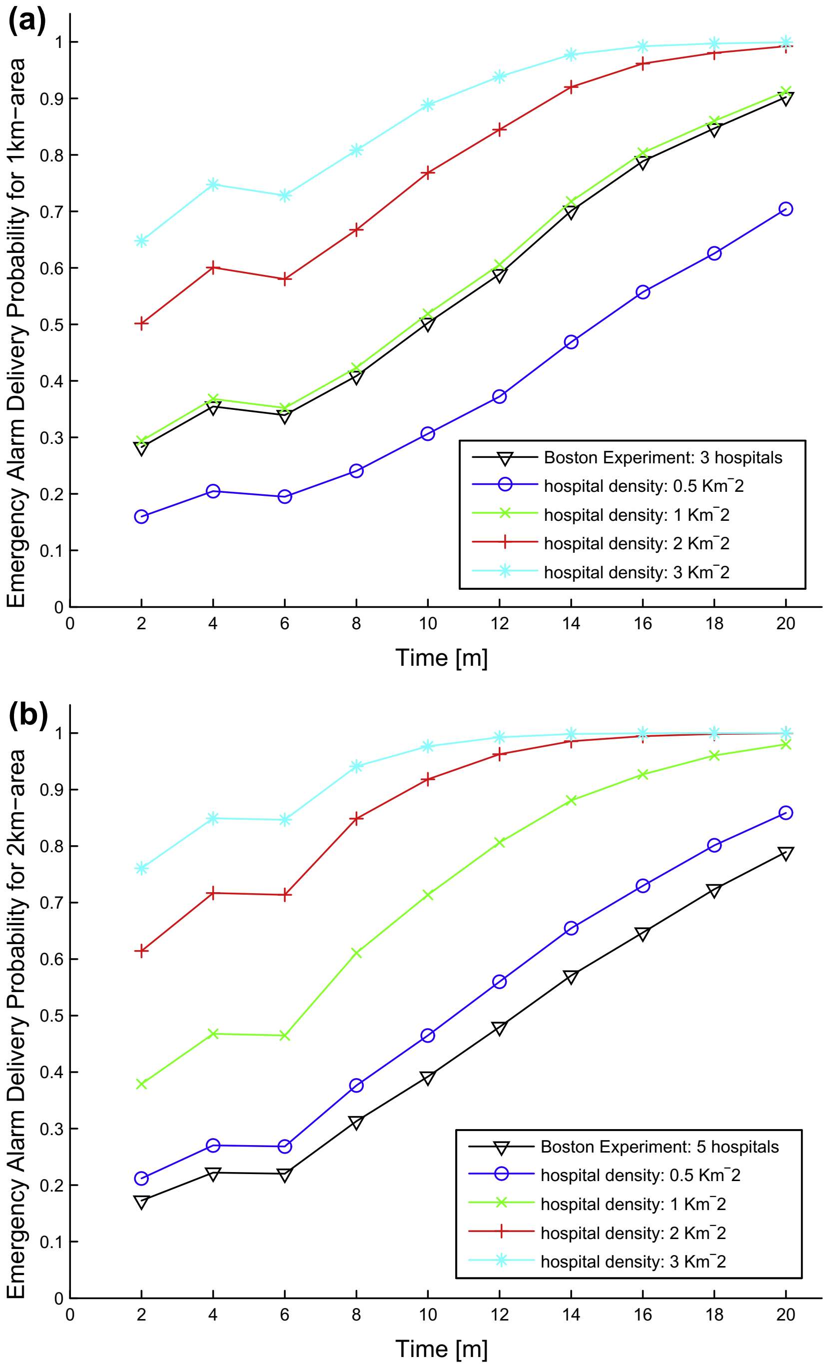

Fig. 3. Emergency alarm message delivery probability as function of time: average of 50 simulations (a) Delivery probability for 1-km target area (b) Delivery probability for 2-km target area.

where t is the time elapsed from when the emergency event happens (expressed in minutes), d is the distance threshold (expressed in meters), $A(t,d)$ is the set of mobile phones less than d meters far from the location of the medical emergency event that have successfully received at least one medical alarm message at time t, $N(t,d)$ is the set of mobile phones less than d meters far from the location of the medical emergency event.

By adopting the *frequentist* definition of probability and by assuming uniform distribution of a hospital in the circle area around the emergency event location, we approximated the probability $p(t,d)$ of a medical alarm message being received by a hospital located less than d meters far from the location of the medical emergency event, in less than t minutes as:

$$p(t,d) \cong r(t,d). \quad (2)$$

we note that in Eq. (2) the equality holds when $|N(t;\, d)|$ goes to infinity. Finally, we comput the probability $p(t;\, d)$ of a medical alarm message being received by at least one of the n hospitals located less than d meters far from the location of the medical emergency event in less than t minutes as:

$$p(t,n) = 1 - \prod_{k=1}^{n}(1 - p(t \cdot d)). \quad (3)$$

For our purpose we consider the actual hospital distribution in the described area, as shown in Fig. 1: three hospitals in about 3.14 km^2, corresponding to a density roughly equal to 1 hospital/km^2.

Moreover, in order to evaluate the effect of different hospital densities on the alarm reception, we investigated densities varying from 0.5 to 3 hospital/km^2.

3. Results

For our simulations, a medical emergency event originating at the Concert area, Hatch Shell, at 05:00 pm, was analysed. We examined the results of the experiment as a function of:

- Time elapsed from the emergency event.
- Radius of the target area, i.e., 1 or 2 km.
- Number of hospitals equipped with a medical room in the target area.

Fig. 3 shows the evaluated mean probability with the two considered area extensions: as expected the delivery probabilities increase as time and hospitals density increase.

For all the considered settings, the majority of nodes are noticed in less than 20 minutes. This time decreases as the number of nodes acting on medical emergency (in our case, the hospitals) increases.

For the considered Boston scenario (line with triangular dots), the time needed to guarantee a noticed hospital in an area of 1 km radius with a probability of 60% results in about 12 minutes, close to the delivery probability obtained with a hospital density equal to 1 hospital/km^2. For the same scenario but in a wider area (2 km radius), our simulations show that at least one of the three hospitals could be noticed with the same probability in about 16 minutes.

Notification intervals resulted even higher for a hospital density equal to 0.5 hospital/km^2 hospital distribution: roughly 17 and 13 minutes for a 1 and 2 km radius, respectively.

However, considering a density equal to 3 hospital/km^2, the time-response to reach hospitals, with a delivery probability higher than 70%, resulted less than 4 minutes in a 1 km radius area and even lower (less than 2 minutes) for a 2 km radius area.

4. Discussion

In this study, we simulated a medical emergency event and we analysed the results of the equate communication and raised personal risk. In such a case, the maximum level of information about the status and position of any individual with a medical emergency is valuable in the whole event management.

To mimic the use of a temporary (ad hoc) wireless network for medical alarm dissemination in urban environment we used realistic people mobility patterns.

However even if the simulations were based on realistic human mobility modelling, some limitations have to be considered.

The results clearly showed that the efficacy of the adopted communication paradigm increases as the number of mobile terminals and hospital density increase. Thus, the number of nodes that can potentially act in an emergency situation may not be reduced to just ambulances or hospitals. Particularly, in presence of medical or specialized personnel, the percentage of actors able to play a role during the medical emergency would be greater, reducing the time of the alarm delivery and subsequent intervention.

On the other hand, in rural areas, it is reasonable to expect that the time required for dissemination of medical alarm through an ad hoc network rises, affecting the expectances of positive resolution of patients medical emergency.

In addition, it is important to note that the analysed large-scale event did not involve any emergency situation. Human behaviour might change in case of emergencies (Bagrow et al., 2011), however, our analysis relied on realistic human spatial distribution over large areas and simulated medical alarm dissemination opportunities during special events, which do not involve large changes in mobility patterns.

5. Conclusions

In medical emergency events, the congestion or failure of network infrastructure is more than a chance. The approaches proposed in scientific literature generally assume the presence of infrastructure-based communication network or medical/

rescue personnel on the emergency site. However, the opportunity to disseminate an alarm via wireless connections of mobile phones may represent one of the few possible alternatives for requesting medical intervention from the nearest hospital.

The encouraging results of this study confirmed that in urban scenarios, the people mobility and the density of beneficial actors (hospitals, ambulances, etc.) could assure timely alarm dissemination.

The solution explored has therefore the potential to be routinely utilized in public gatherings, concerts, football matches as well as other people aggregation.

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