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Disruption Tolerant Communications for Large Scale Emergency Evacuation

Gokce Gorbil and Erol Gelenbe
Imperial College London
Department of Electrical & Electronic Engineering
Intelligent Systems and Networks Group
London, SW7 2AZ, United Kingdom
Email: {g.gorbil, e.gelenbe}@imperial.ac.uk

***Abstract*—In urban emergencies and disasters, emergency support systems enabled by ubiquitous computing and mobile communications can prove very beneficial by providing alerts, guidance and other crucial information to civilians and emergency responders. However, the communication infrastructure that such systems depend upon is usually adversely affected in emergencies due to failures or congestion. Thus we consider the problem of providing emergency support when existing communication infrastructure is unavailable. We propose the use of opportunistic communications (Oppcomms) among mobile devices for the dissemination of emergency information. With Oppcomms, devices exchange messages at a close range of a few to tens of meters with limited or no infrastructure and messages are carried over multiple hops in a "store-carry-forward" manner by exploiting human mobility. We present an emergency support system (ESS) based on Oppcomms to provide evacuation guidance to civilians in large-scale urban emergencies in the absence of other means of communication. We evaluate the performance of ESS with simulation experiments of large-scale evacuation of a district of London, UK. Our evaluations show the improvement Oppcomms can offer.**

***Keywords*-Opportunistic communications; delay tolerant networks; emergency simulation; disaster management; evacuation support systems.**

I. INTRODUCTION

In large-scale emergencies, people in a wide area need to be quickly and safely evacuated to safe zones. However, modern mobile communication infrastructures that normally keep people connected and informed "on-the-go" have repeatedly proved to be unreliable and unavailable during and after large-scale disasters. Therefore increasingly sophisticated distributed information technologies have been suggested to improve the resilience of the outcome of emergencies [1]. Failure of the mobile network has been observed in many recent disasters, e.g. the 2011 Tohoku earthquake and tsunami and the following man-made disaster at Fukushima nuclear power plant in Japan [2], and Hurricane Sandy in 2012 [3]. In addition to failures, mobile networks are overloaded during disasters due to unusually heavy demand, preventing access to most users. Thus failures and congestion of the mobile network can be expected to significantly hamper communications and emergency response efforts, including evacuation.

Thus in this paper, we consider the challenge of providing emergency support even when the standard wired and wireless communication infrastructure becomes unavailable, and propose the use of Opportunistic Communications (Oppcomms) among mobile devices carried by civilians to provide a disruption-tolerant communication infrastructure. In such an emergency Evacuation Support System (ESS) based on Oppcomms, each mobile device will maintain an internal view of the area and the conditions, which is updated by emergency messages exchanged through Oppcomms. Using its internal view, each device presents step-by-step navigation directions to its user for evacuation purposes. We evaluate the performance of ESS for large-scale evacuation of urban areas using a district of London, UK as an example scenario. Our simulation results show the improvement that Oppcomms can offer.

In our recent work [4] we have already proposed the use of Oppcomms together with sensing as a tool to enhance the emergency evacuation of buildings and other structured or confined spaces, and compared indoor performance of ESS with an evacuation system based on fixed and networked decision nodes in [5,6]. Furthermore, the resilience of Oppcomms to node failures and to network attacks that may occur as part of a more complex emergency have been evaluated in [7,8].

This paper differs from our previous work because we evaluate how Oppcomms can improve emergency evacuation in *large-scale outdoor* scenarios with an appropriately *higher number of civilians*. The results we obtain are *also distinct* from our previous findings since the layout of the outdoor urban area and the number of participants will significantly alter the outcome of an evacuation with and without Oppcomms. In particular we observe that, despite the much larger scale and the much larger number of humans, Oppcomms operate in a satisfactory manner to support emergency evacuation, even though the average time delay for communications will significantly increase due to the reduced density of participating nodes.

II. RELATED WORK

Oppcomms offer a means of communication among mobile devices without existing infrastructure and with inter-

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mittent connectivity [9]. The opportunistic network (oppnet) formed is a type of delay tolerant network (DTN) where contact opportunities are not known a-priori. In oppnets, nodes may be disconnected from the network for long periods of time, and end-to-end paths between source and destination nodes are unlikely to exist. Therefore, nodes employ the "store-carry-forward" paradigm for communicating: packets are carried on behalf of other nodes in local storage and forwarded during opportunistic contacts. In this way, data is incrementally stored and moved through the network without first establishing an end-to-end path. Oppnets exploit node mobility to bridge gaps in the network, but message delivery is not guaranteed and delivery may take a long time [10].

We next present an overview of related work that investigates the use of Oppcomms and DTNs for emergency management. Most of them evaluate how Oppcomms can be used for dissemination of emergency messages, and we are among the first, if not the first, to consider the application of Oppcomms specifically for evacuation support. Bruno et al. [11] propose the use of an oppnet in order to "glue" together parts of the surviving communication infrastructure after a disaster. The main idea is to combine all the heterogeneous communication resources available via opportunistic overlays. Saha et al. [12] provide an evaluation of multi-copy opportunistic routing protocols for the dissemination of emergency messages using a disaster mobility model. A modified epidemic routing protocol is proposed in [13] for the dissemination of emergency messages among smartphones when cellular infrastructure is unavailable, focusing on prioritization of messages for one-way unicast communications. We also employ prioritization to ensure more recent information is disseminated faster than old information. The authors of [14] present the design of a DTN architecture for the Android system in order to support Oppcomms among smartphones. Oppcomms are then used to establish communication channels between emergency control centers and registered users when other infrastructure has failed. Winter et al. [15] propose the use of short-range communications similar to Oppcomms for collaborative evacuation based on local knowledge. They focus on evaluating the utility of sharing local knowledge (hazard and area information) via local communications and evaluate the improvement in evacuation outcome using simulations of artificial graphs that represent the area. Among the works reviewed, [15] is the most similar to our presented approach and their results support our findings in Sec. IV that sharing hazard information considerably improves evacuation. We would like to note that other works in the field of emergency navigation and evacuation, e.g. [16,17], have investigated the use of fixed communication networks, such as wireless sensor networks, to monitor the hazard and to guide evacuees. The work presented in this paper is considerably different than such works due to the mobile and resilient nature of the network used to enable evacuation support.

Figure 1: The emergency area used in our evaluation and its graph representation. Also shown are the initial starting points of the hazard and the area exits.

III. OPPORTUNISTIC COMMUNICATIONS FOR EMERGENCY EVACUATION SUPPORT

Our proposed emergency Evacuation Support System (ESS) consists of mobile devices called **communication nodes (CNs)** carried by civilians. Smartphones or similar battery-powered communication devices would serve as CNs. We assume that CNs have short-range (from a few to tens of meters) wireless communication capability, e.g. Bluetooth or WiFi, a location provider such as GPS, a processor and some memory for storing the area graph and the messages received via Oppcomms. We represent the emergency area as an undirected connected graph $G(V, E)$, where vertices V are locations people can occupy, such as intersections and points along roads, and edges E are physical paths that can be taken by people to move from one location to another. This graph is in essence a discrete approximation of the area of interest and each CN stores a local copy of the graph. We assume that the area graph has been obtained prior to the emergency, using either offline methods (e.g. the graph comes pre-installed in the device) or online methods while other communication infrastructure was still available (e.g. the device automatically downloads and stores a cached copy of the graph from a trusted source on the Internet). Although Oppcomms can be used to disseminate an initial copy of the graph to CNs that do not already have one, we leave evaluation of this scenario as future work and assume that each CN has a local copy when the emergency starts. All updates to the graph that occur as a result of the emergency are disseminated by Oppcomms. Figure 1 shows the emergency area used in our evaluation and its corresponding graph representation.

Each CN initializes its graph with multiple costs associated with each edge $(i, j) \in E$. The physical distance between the end points of the edge is represented by $l(i, j)$, while $h(i, j)$ represents the hazard intensity along the edge. The hazard intensity is an indication of the "hazardousness" of the edge; it may come from quantitative sources, such as sensors providing measurements, or from qualitative sources such as humans reporting their perceived seriousness of the hazard, e.g. light/heavy flooding, thin/thick smoke, etc. We discuss this issue in more detail later in this section. The "effective" cost of the edge is represented by $L(i,j) = l(i,j) \cdot h(i,j)$, combining distance and hazard intensity to express the consequent cost of this edge being traversed by a civilian. When there is no hazard along the edge, $L \equiv l$.

Safe and quick evacuation of people requires up-to-date information on conditions that may affect evacuation, such as road blockages, congestion, and any hazards. Three types of information sources could be used in ESS: (i) pre-deployed sensors in the area, (ii) sensors embedded in CNs, and (iii) the people. In the near future, "smart cities" will have pre-deployed static or mobile sensors for non-emergency purposes such as environmental or traffic monitoring. These **sensor nodes (SNs)** can be exploited during emergencies to provide hazard and related information as part of ESS. Such SNs would need to have an independent power supply in order to continue operating in case of a power grid failure and they would need to have wireless communication capability in order to relay their measurements to CNs in an opportunistic manner. In cases where devices dedicated to emergency support are used as CNs, they would be equipped with sensors to monitor the environment and would generate their own observations. A final source of information would be the civilians in the area: they would provide basic information on the hazards and the conditions they observe through their CNs. User-based information would indicate the type and the severity of the hazard. Examples of similar "urban sensing" in unstructured form have been observed in major disasters, for example Hurricane Sandy, where people in affected areas used social media to provide updates and photos on effects of the disaster. Such tendencies can be channeled to generate local knowledge on the hazards, which would be stored in the user's CN to be disseminated via Oppcomms.

Each hazard observation is converted by its source CN into an *emergency message (EM)* that contains the location (vertex) of the hazard in the area graph, the hazard intensity and the timestamp of the observation. The location and the timestamp of the measurement are based on the source of the observation, either an SN or a CN. EMs are disseminated among CNs using Oppcomms, which the CNs use to update their internal views, i.e. their area graphs and edge costs. Since Oppcomms do not guarantee that each EM will be received by every CN and since message delivery may take a long time, each CN has a partial view of the emergency. The first local observation of a hazard or the first received EM serves as an alert indicating to a user that she needs to start evacuation. Then, using its local view, her CN computes a *least-cost path* from its current location (vertex) to all area exits and uses the least-cost path among these in order to direct its user to safety. Our implementation uses Dijkstra's shortest path algorithm with effective edge costs L. Therefore, the least-cost path jointly minimizes the hazard and the distance of the path; we give greater weight to avoiding hazards than minimizing distance in this process. The least-cost path is re-computed when the graph is updated as a result of a received EM or a local observation. A CN uses this least-cost path and its current location in order to provide personalized step-by-step navigation directions to its user as she evacuates the area. We assume that a CN uses satellite-based localization, e.g. GPS, to locate itself within the area graph. If there are SNs in the area, they can assist CNs to more accurately and more quickly find their positions. We leave detailed discussion of this option as future work.

EMs are very short messages containing information that is relevant to all evacuees in the area. Therefore, each EM is destined for all CNs. Considering the "one-to-all" nature of EMs, ESS employs a *prioritized* version of *epidemic routing* [18] for Oppcomms. Epidemic routing is a simple flooding-based routing protocol that reduces communication overhead by transferring only those messages which are not held by a node during contacts. This is achieved by first exchanging a summary bit-vector of messages held by nodes. Note that in practice, EMs would be packaged into packet bundles to improve communication efficiency. In order to efficiently store EMs with limited memory, each CN employs a *timestamp-based priority queue*, where EMs are prioritized according to their (creation) timestamps, with newer EMs given higher priority during contacts and in storage. EMs are exchanged in priority-order during contacts to improve the probability of new EMs being disseminated, considering that contact durations may not be long enough for the exchange of all messages between two CNs. Similarly, oldest messages are dropped first when storage is full.

IV. EVALUATION

We have evaluated the feasibility of Oppcomms to enable emergency evacuation support using simulations of large-scale evacuation of pedestrians in the Fulham district of London, UK. The size of the simulated area shown in Fig. 1 is $\{2.6 \times 1.8\}$ km^2, and the parks in the area are designated evacuation points. We assume that all means of communication have broken down when the emergency starts. We simulate three evacuation scenarios:

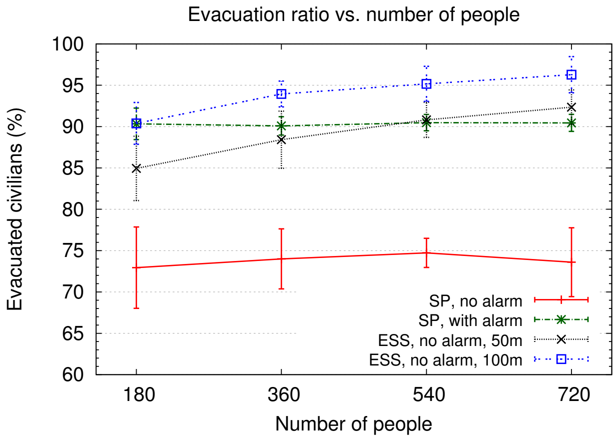
- ESS: We assume that civilians in the area are equipped with CNs that participate in Oppcomms, and CNs notify and direct their users to safety.
- SP$^-$: This scenario simulates shortest path evacuation without Oppcomms. We assume that people learn of the hazard when they encounter it and consequently evacuate the area using the least-cost path. Since there are no Oppcomms, people only know of the hazards they physically encounter.

- SP^{+}: This is like the SP^{-} scenario described above, with the addition of a central alarm that informs everyone as soon as the emergency starts.

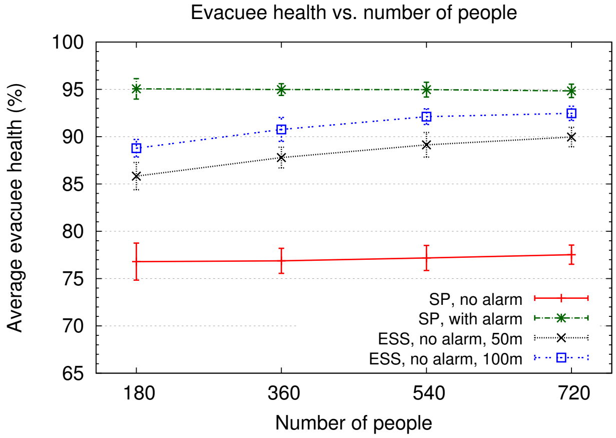
We assume that CNs have a maximum communication range of 100m, and that each CN can store 100 EMs for Oppcomms. Each EM is 50 bytes on average, excluding protocol headers. We simulate wireless communications that employ CSMA-CA at the MAC layer and assume a maximum application data transfer rate of 100 kbits/sec between CNs. We do not explicitly simulate the physical layer, but we take into account contention for the wireless medium as accessed through CSMA-CA. People are initially distributed randomly in the area and they follow a probabilistic mobility model before they start evacuation. The mobility model we use is similar to the random waypoint mobility model but people follow the shortest path between two locations instead of following a straight line. People move at a speed of 1.39 m/sec (5 km/hour) and we simulate physical congestion during civilian movement. The simulated hazard starts simultaneously at multiple locations in the area; the starting locations are shown in Fig. 1. We simulate fire and associated effects such as smoke, and the hazard probabilistically spreads in the area along graph edges following a Bernoulli trial model. The exposure duration, distance to the hazard and the hazard intensity influence its effect on the health of civilians. The maximum health is 100, and a person with a non-positive health is assumed to have perished.

We use the Distributed Building Evacuation Simulator (DBES) [19] for our evaluation. DBES is an agent-based discrete-event simulation tool designed to support evaluation of emergency systems and scenarios in urban spaces. It enables distribution of a scenario across multiple networked machines. We divide the simulated area into 18 sub-areas and assign each to a separate simulation running on a different physical machine, which interact and coordinate in order to simulate the whole area. Each data point in the presented results is a mean of 10 simulation runs. Each run represents a different initial distribution of the civilians, the movement patterns, and the hazard spread pattern. Results are presented with their 95% confidence intervals. We vary the number of people from 180 to 720; these numbers are admittedly lower than the expected population of the simulated area, but these lower numbers reflect that not everyone in the area will have a CN that can participate in Oppcomms.

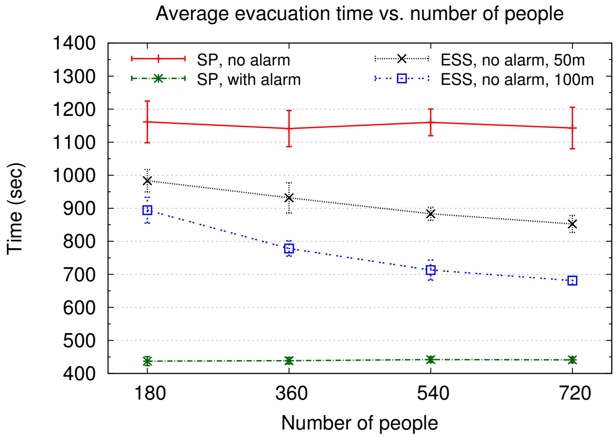
Figure 2 compares the three evacuation scenarios with different population densities, looking at the evacuation ratio $|S|/|N|$, the average evacuee health $\sum_{s \in S} h(s)/|S|$ and the average evacuation time $\sum_{s \in S} t(s)/|S|$. N is the set of all people in the area, S is the set of people who successfully evacuate the area, $h(s)$ is the health of an evacuee $s \in S$ when she reaches a safe zone, and $t(s)$ represents how long it took evacuee s to reach safety from the time the emergency started. In SP^{-} and SP^{+} scenarios, the population



(a) Evacuation ratio

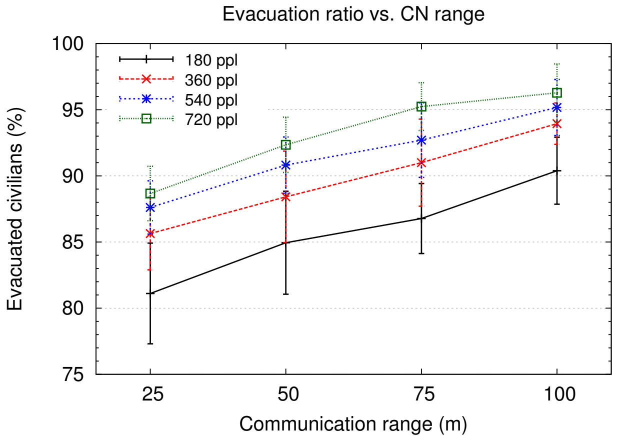


(b) Average evacuee health

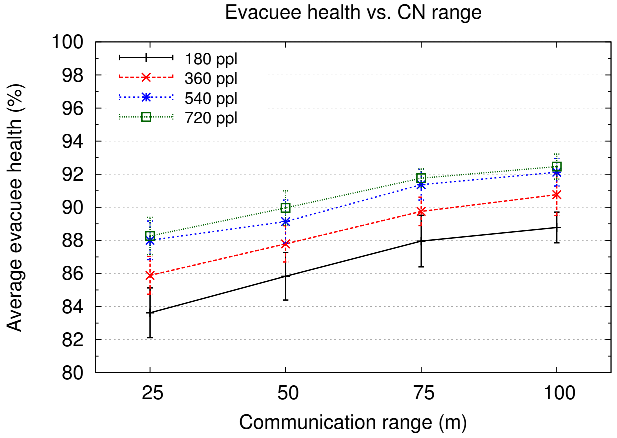


(c) Average evacuation time

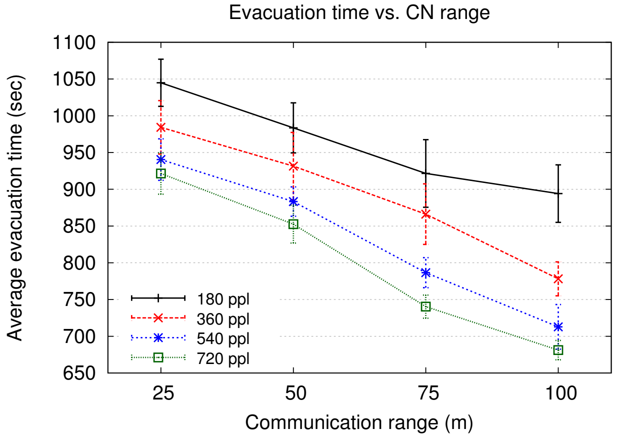
Figure 2: Evacuation performance of ESS, SP^{-} and SP^{+} with different population densities, communication range = 50m and 100m.



(a) Evacuation ratio

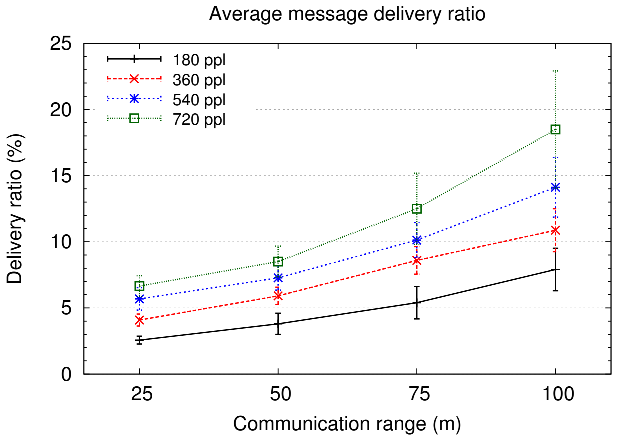


(b) Average evacuee health

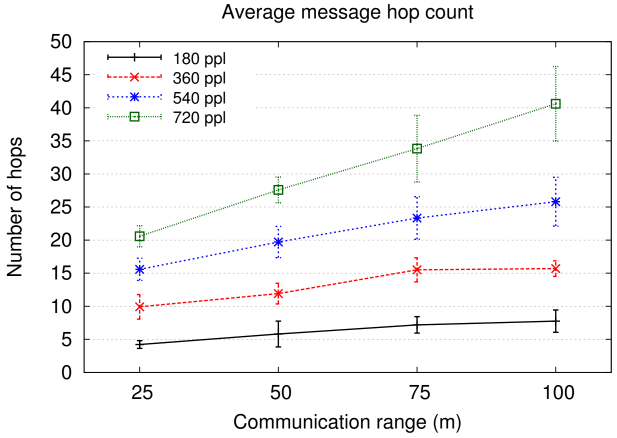


(c) Average evacuation time

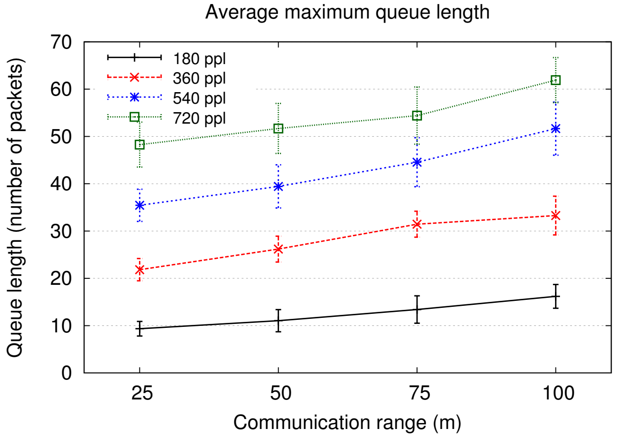
Figure 3: Evacuation performance of ESS with different population densities and communication ranges.



(a) Delivery ratio



(b) Average hop count



(c) Maximum queue length (average)

Figure 4: Communication performance of ESS with different population densities and ranges.

density does not have a significant effect on the evacuation ratio or on the average evacuee health due to the lack of information sharing among people. SP$^-$ has the worst evacuation performance due to its lack of early notification (i.e. alarm) and of sharing hazard information. Having early notification significantly improves the evacuation performance as observed with the SP$^+$ scenario. While lacking a central alarm, ESS provides significant improvement over SP$^-$ in the evacuation performance since nodes share hazard information via Oppcomms. As expected, the performance of ESS improves with better oppnet connectivity, which may be due to more people in the area (i.e. higher density) or due to longer communication range. Figure 3 presents a clearer view of the impact of the communication range on performance. ESS has worse evacuation ratio than SP$^+$ when the number of people and the communication range are very low (see Fig. 2a). The poor performance of ESS with considerably low connectivity indicates that using Oppcomms for emergency evacuation would provide the greatest benefit in urban areas with dense populations.

ESS has better evacuation ratio than SP$^+$ when the oppnet connectivity is good, but its average evacuee health is lower than that of SP$^+$ (see Fig. 2b). This is because with ESS, some of the evacuees inevitably encounter the hazard due to partial information and high message delays, and therefore their exposure to the hazard is higher. However, these observations are not wasted and others are informed of the hazard through Oppcomms, which improve the evacuation ratio at the expense of the average evacuee health. In contrast, such observations are "wasted" in the SP$^+$ scenario since information is not shared, resulting in more casualties.

Results on the average evacuation time, given in Fig. 2c, show that SP$^+$ has the quickest evacuation time due to its alarm, while SP$^-$ has the slowest due to its lack of any type of alert or of sharing of information. ESS is in between, with improving evacuation time as the oppnet connectivity improves. Figure 3 presents the effect of communication range on ESS performance at different population densities. Since a longer range means more contact opportunities, we observe that the evacuation outcome improves with range. The improvement in the evacuation ratio and the average evacuation time are especially significant.

Figure 4 presents our results on the communication performance of Oppcomms as used in ESS. Let c_i be the number of EMs created by CN i and r_i be the number of *unique* EMs received by i. We calculate the message delivery ratio as $\sum_{i \in N} r_i / (\sum_{i \in N} c_i * |N|)$ since each EM is destined for *all* CNs. The average message delay is the mean of the one-way (from source to destination) delivery delays of all received EMs. The average hop count is the mean of the number of hops taken by all received EMs. The average queue length is the mean of the maximum queue lengths of all CNs, and the maximum queue length of a CN is the maximum number of packets that it held. The average queue length metric is indicative of the storage requirements of Oppcomms and of the communication overhead.

	Number of CNs			
Range (m)	180	360	540	720
25	291.720	367.428	392.215	380.809
50	281.095	362.646	342.022	340.340
75	301.228	328.143	287.483	307.110
100	311.212	271.201	262.616	281.698

Table I: Average message delivery delay (seconds)

The low message delivery ratios observed in Fig. 4a are partly a result of how we defined the delivery metric. But more importantly, they are an indication that most communications happen in local circles, a result that is supported by our data on the average hop count (Fig. 4b) and the average queue length (Fig. 4c). This result is in contrast to our findings on Oppcomms in confined spaces [4,6] due to the larger scale and the spatial layout of the emergency area considered in this evaluation, and due to the comparably lower population densities.

Table I presents the average message delay with Oppcomms; we observe as expected that increasing the communication range decreases delay, except with 180 people when the density of communicating nodes is very low. Message delays with Oppcomms are high compared to traditional networks, since delivery delay is dominated by "storage delay" and the long travel distances mean that messages spend much time in the "carry" phase of the "store-carry-forward" cycle. However Oppcomms still improve the outcome of evacuation. As seen in Fig. 4b, the average hop count decreases with increasing population density and CN range. The relatively short queue lengths in Fig. 4c indicate that ESS is not very demanding in terms of storage space, especially with small message sizes.

V. CONCLUSIONS AND FUTURE WORK

This paper has focused on the role of communication technologies that do not require an infrastructure to operate, and particularly Oppcomms, and on the evaluation of the system based on simulations with the DBES tool. Much work still remains to be done, in particular because the populations involved in an emergency belong to multiple types and classes [20,21], both with respect to their mobility, the roles they play (e.g. emergency personnel) and their access to different communication technologies, and because information is incomplete and imprecise [22]. Furthermore, it would be useful to examine how such technologies can be used in the optimum usage and deployment of emergency response vehicles and personnel [23,24]. It is also important to move towards the use of a broader range of methodologies, including graph theoretic and analytical modelling techniques [25]–[28] so fast performance evaluation and more varied parameter settings may be readily analysed. The manner in which simple evacuation procedures may change when one uses Oppcomms [29] should also be considered.

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