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Opportunistic Communications for Emergency Support Systems

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Abstract

Opportunistic communications (oppcomms) use low-cost human wearable mobile nodes allowing the exchange of packets at a close range of a few to some tens of meters with limited or no infrastructure. Typically cheap pocket devices which are IEEE 802.15.4-2006 compliant can be used and they can communicate at 2m to 10m range, with local computational capabilities and some local memory. In this paper we consider the application of such devices to emergency situations when other means of communication have broken down. This paper evaluates whether oppcomms can improve the outcome of emergency evacuation in directing civilians safely. We describe an autonomous emergency support system (ESS) based on oppcomms to support evacuation of civilians in a built environment such as a building or supermarket. The proposed system uses a fixed infrastructure of sensor nodes (SNs) to monitor the environment. Hazard information obtained via SNs is disseminated to the individuals, and they spread among the people who are located in this built environment using oppcomm devices carried by these people. The information received by these people can then guide them safely to the exits as the emergency situation evolves over time. We evaluate our scheme using a distributed multi-agent building evacuation simulator (DBES) in the context of evacuation scenarios of a multi-storey office building in the presence of a fire that is spreading. The results show the degree of improvement that the oppcomms can offer.

Keywords: Opportunistic communications, delay tolerant networks, building evacuation, emergency support and management

1. Introduction

In emergency circumstances, both the people and vehicles that are implicated in the area where the emergency is taking place, and those that are outside this area but may be heading to it, need to be rapidly informed and routed safely. Thus in this paper, we describe an **autonomous emergency support system (ESS) based on opportunistic communications** (oppcomms) to support evacuation of civilians in urban

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emergencies. The proposed system uses opportunistic contacts between wireless communication devices carried by civilians to gather information regarding the current situation and disseminate messages in order to guide the evacuees safely to the exits. Our proposed system is targeted for densely populated urban environments.

Related work in civilian navigation and emergency evacuation includes work by Tseng et al [1] who propose a distributed navigation algorithm based on the temporally ordered routing algorithm (TORA) in order to guide civilians in a building with a 2D layout during an emergency. In [2] the work in [1] is extended to 3D indoor building environments by adding stairway nodes to connect different floors, while in [3] a distributed WSN-based building evacuation algorithm that takes into account the expected spread of the hazard inside the building is discussed. In [4, 5] congestion during evacuation is taken into account; in [4], how to guide rescuers to critical areas in the building is also examined. Other work [6] presents an autonomous indoor navigation system based on mobile phones that assumes a WSN to monitor the building and receive updates on a dynamic hazard, with a centralized emergency guidance system.

Previous work by our group [7, 8] proposes a distributed decision support system (DDSS) for building evacuation, where static decision nodes (DNs) with communication and processing capabilities are installed in the building and provide directions to civilians in their vicinity, either via dynamic signs or wireless communications. DNs form a network and disseminate information regarding the hazard and evacuation paths in a distributed manner based only on local information, and a distributed update algorithm is executed periodically by the DNs, where each DN communicates with its neighbors to send its current hazard and path metrics.

The autonomous emergency support system proposed in this current paper considers the same problem, but instead of using static DNs, it relies on oppcomm devices carried by civilians to gather and disseminate information on the current situation. Oppcomms use low-cost human wearable mobile nodes allowing the exchange of packets at a close range of a few to some tens of meters with limited or no infrastructure. Typically cheap pocket devices which are IEEE 802.15.4-2006 compliant can be used and they can communicate at 2m to 10m range, with local computational capabilities and some local memory. In this paper we consider the application of such devices to emergency situations when other means of communication have broken down.

Thus this paper evaluates whether oppcomms can improve the outcome of emergency evacuation in directing civilians safely. We describe an autonomous emergency support system (ESS) based on oppcomms to support evacuation of civilians in a built environment such as a building or supermarket. The proposed system uses a fixed infrastructure of sensor nodes (SNs) to monitor the environment. Hazard information obtained via SNs is disseminated to the individuals, and they spread among the people who are located in this built environment using oppcomm devices carried by these people. The information received by these people can then guide them safely to the exits as the emergency situation evolves over time. We evaluate our scheme using a distributed multi-agent building evacuation simulator (DBES) in the context of evacuation scenarios of a multi-storey office building in the presence of a fire that is spreading. The results show the degree of improvement that the oppcomms can offer.

The approach proposed here is significantly different from our group's previous work regarding DDSS, since hazard information is disseminated over an opportunistic network formed by communication nodes (CNs) in the ESS. Furthermore, each civilian is guided by her own CN, which locally calculates the best evacuation path based on current information. This work is also an investigation of the interdependence between human mobility and communications in the context of emergency evacuations, and is also one of the first studies that examines how oppcomms can be used to improve evacuation outcome in case of a dynamic hazard in a building.

2. System Description

Our proposed system, ESS, consists of **fixed sensor nodes (SNs)** and **mobile communication nodes (CNs)**. SNs are pre-deployed at fixed locations in the building and monitor the environment for possible hazards. Each SN has a sensing unit that senses its immediate area (e.g. for contaminants, smoke, or excessive heat) and has short range (1m to 2m) wireless communication capability so it can directly communicate with CNs in range. SNs have very low memory capacity and processing power, i.e. as much as necessary to perform the sensing and communication functions, and are assumed to be energy-limited, making power consumption a major consideration for SNs. Therefore, SNs *do not* perform any data storage, processing or decision making and are only utilized for environment monitoring and civilian localization, i.e. to tell the portable CNs about *where* the mobile user is in the building. It is important to note that the SNs do not form a conventional wireless sensor network and hazard information is not disseminated among SNs. This is due to the short communication range and limited energy and physical capabilities of SNs.

Each civilian is equipped with a hand- or pocket-held device, with storage and processing capacity that would be equivalent to a mobile phone or similar unit, capable of short-range (~2-10m) communication. These communication nodes (CNs) form a network in an opportunistic manner as devices come into contact. Certain nodes may be placed in fixed locations, e.g. on walls, for additional coverage. Oppcomms enable the dissemination of messages in order to gather and convey information for situational awareness, such as the condition and location of the hazard. Oppcomms are characterized by the "store-carry-forward" paradigm [9] where CNs carry messages in local storage, and then forward it to others as they get within communication range as a result of human mobility. Thus, the message is delivered to its destination via successive opportunistic contacts. Because the network may be disconnected for long periods of time, carrier nodes may store messages for lengths of time, and the delivery of messages to destinations is not guaranteed. The ESS design assumes that each CN will (a) store the graph representation of the building that is described below, and (b) be able to carry out the computations that the ESS needs, sense other CNs in its vicinity, and carry out short range store-and-forward packet reception and transmission for oppcomms.

The building is represented as a graph $G(V, E)$; vertices V are locations where civilians may congregate and move and edges E represent path segments that civilians may follow. Edges have multiple costs associated with them. The length $l(i, j)$ of an edge $(i, j) \in E, i, j \in V$ represents the physical distance between locations i and j. $h(i, j)$ is the perceived hazard intensity along edge (i, j). The effective length of (i, j), calculated as $L(i, j) = l(i, j) \cdot h(i, j)$, is a joint metric combining the physical distance and the hazard. When there is no hazard, $h(i, j) = 1$, so $L(i, j) = l(i, j)$. With increasing hazard, $h(i, j)$ and $L(i, j)$ will increase to reflect the risk. Each edge (i, j) also has a *last-update-time* field $t(i, j)$. The building graph is known for a building since its layout and edge lengths will be static and therefore it can be created once and stored for later use. Each CN stores in local memory the building graph, which is obtained and installed through a trusted source (e.g. the company intra-net). Updates to the building graph which may arise due to rare changes to the layout can be disseminated to CNs through the same trusted mechanism.

Each SN has a unique device ID, a local clock and a location tag that corresponds to its position in the building. SNs periodically take measurements of their surroundings and a hazard is detected when a significant measurement is observed (e.g. existence of smoke, or high temperature). Each measurement is stored until it is over-written by a newer measurement. Each hazard observation creates a new **emergency message (EM)** that includes the location of the SN, hazard intensity, device ID and observation timestamp. EMs, which are identified by their *(device ID, timestamp)* pair, are created by SNs as a result of hazard observations and forwarded to CNs in communication range. In addition to monitoring the environment, SNs are also used to locate civilians. CNs receive **localization messages (LMs)** from SNs via single-hop communications during movement that indicate the current position of the CN. Each LM contains the device ID, location tag and message creation timestamp, and a CN that receives an LM can locate itself in the building through the location tag in the message. The actual position of a CN is therefore approximated by its location on the building graph, i.e. its corresponding graph vertex.

Each EM is a hazard measurement observed by an SN, containing the intensity, location and time of the observation. An SN sends its EM to CNs that come within communication range via single-hop communication. CNs then use oppcomms to disseminate EMs to other CNs, which are used by CNs to update the edge costs on their local graph. Each CN uses its local graph, edge costs and current position in the building to compute a shortest path from the current location to the nearest exit. All EMs are disseminated among all CNs in the system, i.e. each EM is sent *network-wide*. The first EM received by a CN indicates that there is a hazard in the building; upon reception of the first EM, the CN alerts its user of the existence of the hazard and starts the evacuation process. This alarm can be in the form of a physical (e.g. vibration) and audio-visual signal from the CN. Edge costs are updated when the timestamp of the received EM is newer than the last update time of the edges as recorded by the receiving CN; this prevents old events over-writing new ones. When edge costs are updated, the CN updates the shortest path (SP) from its current location to the nearest building exit. As the effective edge lengths (i.e. $L(i, j)$ values) used during SP calculation are a combination of the physical distance and hazard intensity between two locations, the "shortest" path minimizes travel distance while avoiding dangerous areas in the building. The SP is found by executing Dijkstra's SP algorithm from the current vertex to each building exit, and then choosing the path to the nearest exit as the evacuation path. When the CN updates its position in the building, it also updates the directions given to the user based on its current location and SP.

Most data forwarding and routing protocols for opportunistic networks (oppnets) try to achieve a balance between message delivery ratio and resource consumption [10, 11]. For the dissemination of EMs, which are very short in nature, a high delivery ratio and low message latencies are critical. Furthermore, each EM is intended for all CNs in the system. Considering these requirements, we have chosen to employ **epidemic routing (EpR)** [12], which is a flooding-variant forwarding scheme that disseminates multiple copies of a message over the network mimicking the spread of an infectious disease. Although EpR is one of the first routing protocols proposed for oppnets, it is quite suited for the ESS due to its flooding-based approach, high message delivery ratios and low message latencies [13].

CNs employ *timestamp priority* for network storage management, where messages with the earliest creation timestamps are dropped from the queue when the queue is full. There is an exception to this rule in the case of reception of a message m_{new} with the same location and newer timestamp than a message m_{old} already in the queue. In this case, instead of dropping the message with the earliest timestamp in the queue, m_{old} is dropped and is replaced by m_{new}. This strategy supports CNs with limited network storage capacities and is the least disruptive in ESS operation.

3. Experimental Evaluation

We present an evaluation of the proposed ESS using the multi-agent distributed building evacuation simulator (DBES) [14]. We have extended the DBES by adding the capability to simulate opportunistic communications. In our simulations, we assume that in addition to the building graph and edge costs, each CN can store 100 EMs for communication purposes. CN data transfer rate is 100 Kbits/sec and the maximum effective CN communication range varies between 2m–10m. We also assume that there are no inter-floor communications. An SN is located at each vertex of the building graph. Each SN uses its most recent measurement for EMs. SN data transfer rate is assumed to be 20 Kbits/sec and the maximum effective SN communication range is 2m. Packet sizes are assumed to be 14 bytes and 10 bytes for an EM and LM, respectively. An IEEE 802.15.4-2006-type MAC layer is assumed (i.e. CSMA-CA without RTS/CTS).

The three-storey building used in our simulations is depicted in Fig. 1. The top two floors contain most of the offices, and the bottom floor is the entrance hall and contains the two exits. The bottom floor is 24m x 45m and the other floors are 24m x 60m. Each area and room in the building (i.e. graph vertex) is assigned a type; these are "office, WC, rest area, lifts, stairs, and generic". The simulated civilians follow a mobility model during normal (i.e. non-emergency) operation, intended to simulate the movement pattern during working hours. Each civilian is assigned an initial office room. After waiting for a time, which simulates working at the office, s/he chooses a random destination within the building, which is *not* of type "lifts, stairs or generic". After moving to and then waiting for a random time at this destination, s/he returns to his/her office to resume working (waiting); this pattern continues until there is an emergency. We have chosen the waiting times so that a civilian will change rooms every 10 simulated minutes on average. The shortest path between two locations in the building is used during normal movement, and the movement speed for each civilian is 1 m/sec within the floors and 0.7 m/sec when traversing stairs. We assume that exposure to the hazard or the current health of the civilian does not affect her movement speed. The simulations take physical congestion into account during human movement, where a build up of civilians at locations, such as stairs and corridors, affects how fast they progress through that area.

The same hazard (fire) with the same seed is used in all the simulation experiments for a consistent evaluation. The fire starts at a location in front of the elevators on the 2nd floor of the simulated building. This is a critical location as it is very near the intersection of the main hallway on the 2nd floor and the

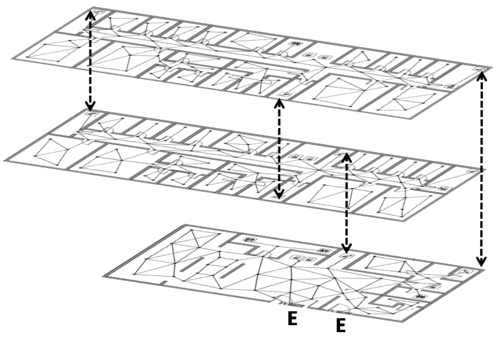
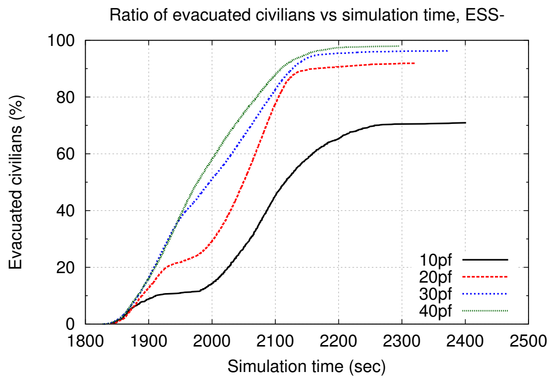
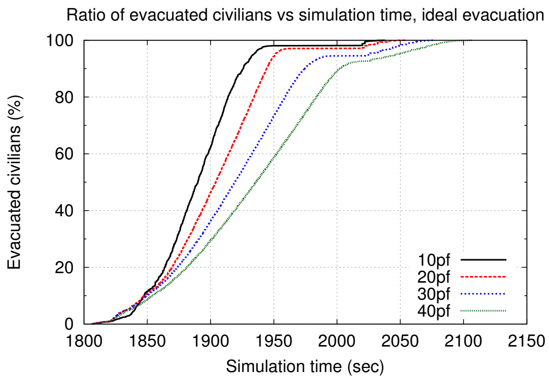


Fig. 1. Three-storey building used in simulation experiments, depicting the inter-floor connections and building exits.



(a) ESS^{-}



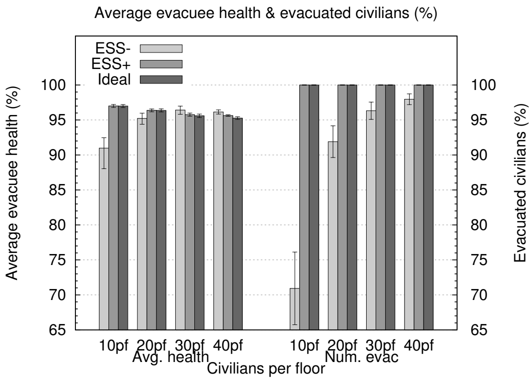
(b) Ideal evacuation

Fig. 2. Ratio of evacuated civilians vs. simulation time, for ESS^{-} and ideal evacuation. The fire starts at time 1800 sec.

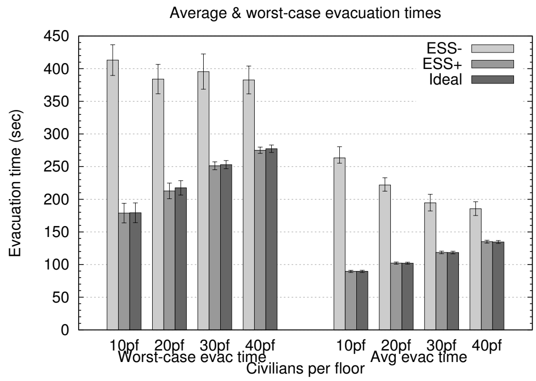
access way to the stairs, and the fire will spread to other areas and floors quickly from this initial location. The fire spreads along graph edges, following a Bernoulli trial model. The fire model and its effects on civilian health have been inspired by [15].

We compare three different scenarios in our evaluation: (i) ESS without alarm, (ii) ESS with alarm, and (iii) ideal evacuation. In the **ESS without alarm scenario (ESS^{-})**, we assume that there is no central alarm in the building (e.g. the alarm has failed due to power failure), so civilians will be alerted and guided only by the ESS. The **ESS with alarm scenario (ESS^{+})** assumes a central alarm that goes off as soon as the hazard is detected, and it alerts all civilians in the building. The ESS then guides civilians who start to evacuate immediately when the emergency starts. In the **ideal evacuation scenario**, we assume a central alarm. In addition, civilians are assumed to know the exact layout of the building and follow the shortest paths to the nearest exits during evacuation. It is also assumed in the ideal scenario that all civilians have perfect and immediate knowledge of the hazard, i.e. that they know the exact location and intensity of the fire as it spreads throughout the building.

In the simulations, the fire starts at time 1800 sec, communication range is set to 6m for CNs and presented results are an aggregate of 40 simulation runs with different civilian-to-office assignments and mobility traces unless stated otherwise. Results include their 95% confidence intervals where appropriate. Figure 2 presents the percentage of evacuated civilians vs simulation time, for ESS^{-} and ideal evacuation with varying population densities (from 10 to 40 per floor). As can be observed, performance of the ESS is dependent on population density. With a very low density of 10 civilians per floor, the oppnet is disconnected most of the time, causing a high number of civilians to be alerted either very late or not at all, and we see that only 71% of civilians are evacuated successfully. The system performs much better for higher



(a) Ratio and health of evacuees



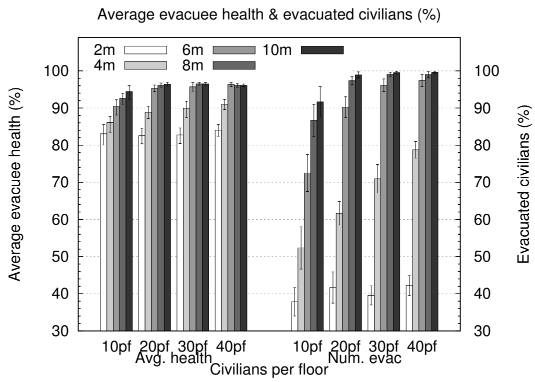
(b) Evacuation times

Fig. 3. Ratio of evacuated civilians, average evacuee health, worst and average evacuation times vs. population density, for all three scenarios.

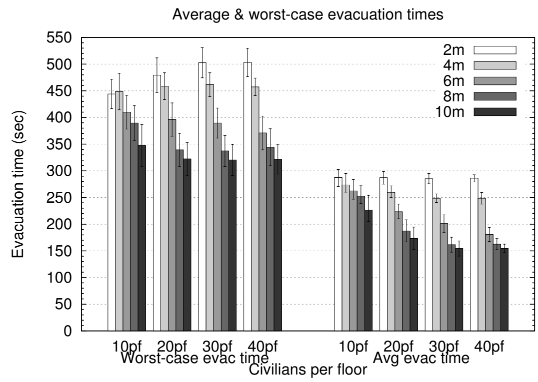
population densities, with evacuation ratios of 92%, 96% and 98% for 20, 30, and 40 civilians per floor, respectively (also see Fig. 3a). The small number of fatalities are caused by civilians located at the very far edges within rooms, which are almost always out of communication range. We observe that in the ideal evacuation scenario, all civilians are successfully evacuated. Interesting to note is the effect of congestion on evacuation times. As civilian density increases, we see that evacuation takes considerably longer; significantly contributing to this phenomenon is congestion on the staircases connecting the floors. The problem of disconnected civilians at lower population densities can potentially be solved by the installation of static CNs at critical locations in the building.

Average evacuee health and ratio of evacuated civilians with different population densities are shown in Fig. 3a for all three scenarios. Each civilian starts with an initial health of 100, which decreases based on the hazard intensity as the civilian is exposed to the hazard (i.e. fire and smoke). It can be seen that ESS guides evacuees via paths that reduce exposure to the hazard, even for low densities. Average evacuee healths better than the ideal scenario are observed in ESS^-; this is due to the fact that only successfully evacuated civilians are counted in this metric, so it is dependent on how many civilians were able to get out of the building alive and therefore should be viewed together with the ratio of evacuated civilians for a more accurate understanding of performance. It is encouraging to note that in ESS^+, the ESS performs as well as the ideal evacuation method. This observation, together with the high evacuee health values observed in ESS^-, supports our claim that the observed fatalities in ESS^- are mostly due to civilians who are alerted very late of the existence of the hazard due to their unreachability. The good performance in ESS^+ also indicates the importance of alerting civilians of the hazard as soon as possible for successful evacuation.

Figure 3b shows the worst-case and average-case evacuation times for the three evacuation scenarios. We observe longer evacuation times in ESS^- as can be expected due to the lack of a centralized and instantaneous alerting system. We again observe similar performance between ESS^+ and ideal evacuation, in this case mostly due to the central alarm present in both scenarios. It is worthwhile to note that even though evacuation takes longer in ESS^- (about x1.5–2 as long as the ideal case on average), observed evacuation ratios and evacuee healths are comparable with the ideal case, especially for high population densities. This is a good indication that the adaptive routing of civilians via ESS performs well during evacuation. One interesting property observed in ESS^- is natural congestion avoidance. Figure 3b shows increasing average evacuation times with increasing civilian density for ESS^+ and ideal evacuation. In these scenarios, all civilians start evacuating at the same time and therefore cause congestion at bottleneck points in the building such as stairs, leading to longer evacuation times. In ESS^-, on the other hand, civilians start the evacuation process at different times, which eases congestion during evacuation. Combined with increased connectivity with increasing density, this translates to decreasing evacuation times in ESS^-.



(a) Ratio and health of evacuees



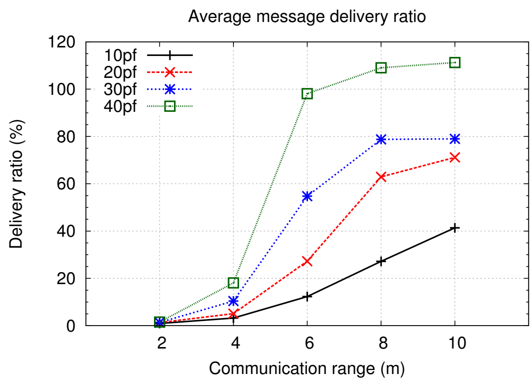
(b) Evacuation times

Fig. 4. ESS performance with different CN communication ranges, scenario ESS$^-$.

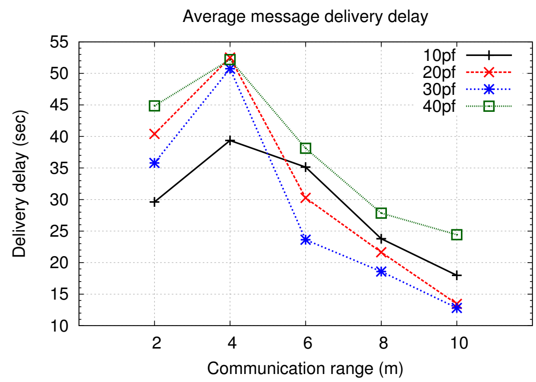
The next set of experiments vary CN communication range between 2m and 10m. Figure 4 shows the effect of CN communication range and population density on performance in ESS$^-$, in terms of ratio of evacuated civilians, average evacuee health, and worst and average evacuation times. It can be observed that with a very small communication radius (e.g. 2m), population density has negligible effect as most of the civilians are always disconnected, resulting in poor system performance. With increasing CN range and density, network connectivity increases with positive effects on performance; diminishing returns is observed as full network connectivity is approached. For the building used in our evaluation, the minimum CN range that produces good ESS performance seems to be 6m. The maximum communication range considered in our experiments, 10m, produces evacuation performance very close to the ideal case (compare with Figs. 3a and 3b), especially with medium-to-high population densities. These results indicate that the proposed ESS is well suited for deployment in urban environments with dense populations; ESS requires larger communication ranges (with accompanying increases in power, energy usage and device cost) for acceptable performance in very sparse populations.

We investigate the properties and performance of the oppnet formed by the CNs in terms of message delivery ratio, delay, hop count and message queue lengths. The following experiments were conducted with the ESS$^-$ scenario. Figure 5a shows the average message delivery ratios for different population densities with increasing CN communication range. We can see a correspondence between message delivery ratio and ESS performance, especially with respect to the ratio of evacuated civilians. This is expected as higher delivery ratios mean more civilians are alerted and kept up-to-date of the situation, resulting in good evacuation performance. However, it is interesting to note that ESS does not require high delivery ratios for good performance, as delivery ratios over 20% correspond to over 80% of the civilians being successfully evacuated (see Fig. 4a). This result is due to the combination of two factors. The first, and most important, is inherent in how ESS operates. A CN does not need to receive all disseminated EMs for successfully guiding its civilian during evacuation. While it is true that a higher ratio of received EMs may lead to better situational awareness, the reception of an EM as soon as the emergency starts and the reception of messages with later timestamps (as opposed to outdated messages relating to old events) are more important than receiving all EMs for good evacuation performance. The second contributing factor is due to how delivery ratio is calculated; the *total* number of CNs is used in the calculation, but there is no practical way to reach 100% delivery ratio during evacuation as civilians (and therefore CNs) who leave the building are unreachable but still contribute to the total CN count. This calculation inevitably leads to understated delivery ratios. Please note that delivery ratios over 100% (for 40pf) is a result of buffer overflows in message storage causing duplicate messages being counted as distinct messages by the nodes.

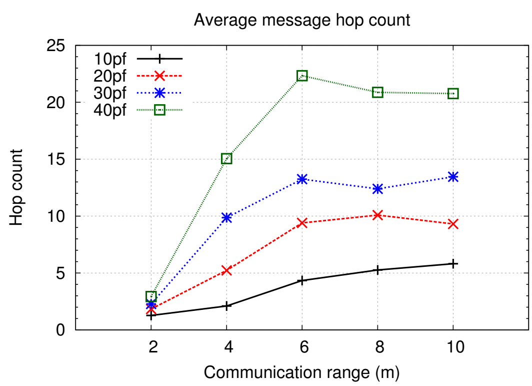
Figure 5b presents average message delivery latencies (one-way) vs communication range under different node densities. We observe that range has a significant effect on message delays, which vary between



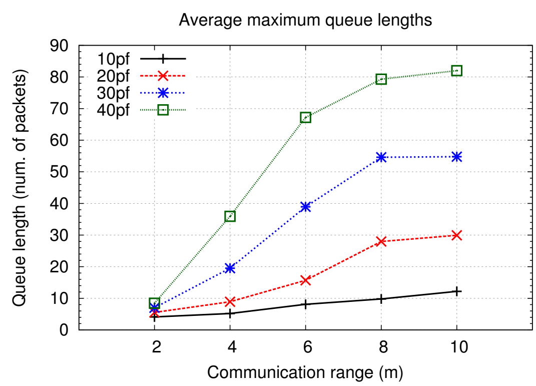
(a) Average message delivery ratio



(b) Average message delivery delay (one-way)



(c) Average message hop count



(d) Average maximum queue length

Fig. 5. Average message delivery ratio, delay, hop count and maximum queue length (in number of packets) vs. communication range, with varying population densities. The restriction of buffer size was removed for Fig. 5d.

13–52 seconds, averaging a 30sec latency. The discrepancy in observed delays when range is 2m is due to the inclusion of only successfully delivered messages in delay calculation and the very low delivery ratios observed for 2m. Apart from this small deviation, it is seen that a longer communication range serves to decrease message delays through better connectivity, while the effect of node density is less significant in comparison. The reason for this can be better understood if we look at the average message hop counts, depicted in Fig. 5c. Contrary to conventional wired networks and MANETs, in oppnets large hop counts do not necessarily mean large message delays. In fact, the opposite trend is observed in our experimental results; for a given node density, increasing communication range leads to higher hop counts and lower delivery delays. This unique feature is caused by the dominance of “storage delay” over transmission and propagation delays (jointly referred to as transfer delay in the rest of the text) in oppnets: a much longer time is spent carrying a message waiting for a contact opportunity (on the order of seconds, depending on node mobility rates) than actually sending the message between two nodes over wireless (on the order of milliseconds). With longer ranges, larger subsets of the oppnet are connected at points in time, which increases the number of nodes a message visits, also increasing its accumulated transfer delay. However, due to better connectivity, contact opportunities are much more frequent, decreasing message storage time, with the end result of a significant decrease in message delivery latency. A higher node density increases contact opportunities without affecting connected subset size as much, meaning messages spend relatively more time in storage and a smaller impact on message delay.

Our final results relate to resource consumption in the oppnet: Figure 5d presents averages of maximum queue lengths used for storing and routing messages by CNs. The restriction on storage size was removed for this experiment to get an accurate picture, meaning that none of the messages were dropped due to buffer overflows. It can be noted that as network connectivity (and the ratio of delivered messages) increases, resource consumption in the oppnet rises, indicated by buffer use of CNs. We see that average buffer lengths range between 4–82 packets for different CN ranges. When CNs are limited to 100 EMs, they would experience buffer overflows only when both communication range and population density are high (i.e. over 6m and 40pf respectively). Even when buffer overflows are observed, only old EMs would be dropped due to the intelligent management of storage.

4. Conclusions and Future Work

We have proposed and described an autonomous evacuation support system (ESS) based on opportunistic communications (oppcomms) to enable the safe and quick evacuation of civilians in urban emergencies. In the proposed system, a fixed infrastructure of sensor nodes (SNs) are used to monitor the environment and to tell civilians where they are inside the building, and civilians are equipped with communication nodes (CNs) which form an opportunistic network (oppnet). The oppnet is utilized to disseminate messages for maintaining situational awareness and alerting and guiding civilians for evacuation during the emergency. A multi-storey office building was used as a case study on how ESS can be deployed in an urban environment. We evaluated the ESS using a multi-agent distributed building evacuation simulation platform (DBES) in a real-life three-storey office building and our experimental results indicate that ESS can successfully support evacuation, especially in dense urban environments.

We are currently working on comparing ESS with other intelligent evacuation systems (e.g. DDSS) in order to better understand the advantages and disadvantages of a mobile node based emergency support system as compared to a static node based one. We also plan on investigating how ESS can be used in conjunction with DDSS, for example as a back-up system. In this paper, we assumed that all CNs operate correctly. In the future, we will look at some security issues that arise when there may be malicious users in the system.

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