Emergency Support System with Directional Extensions

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Abstract

This paper proposes an emergency support system (ESS) with two novel algorithms, a path finding algorithm to guide evacuees during an emergency, and a communication protocol to make the opportunistic communications (oppcoms) more effective (when observing the unnecessarily sent messages). The oppcoms uses low-cost wearable mobile nodes (i.e. smart phones) that can exchange packets at close range without help of an infrastructure. Both algorithms are based on the same idea: always to maintain the direction from hazardous areas to fire exits. The main goal of the ESS is to guide evacuees in a built environment such as in a shopping centre where fire is spreading. Our support system is evaluated with the DBES (Distributed Building Evacuation Simulator) and multiple simulations have been performed with this tool using different parameters. The results show that the enhanced emergency evacuation system can offer significant improvements for the evacuees and can achieve better results when the number of duplications is taken into account.

Keywords

emergency support system, opportunistic communications, building evacuation

1. Introduction

Emergency evacuation is a fundamental part of built environments, for example, sports stadiums, concert halls, buildings in general. This requires computationally intensive complex simulations for planning purposes [1] as well as fast smart techniques to provide on-line guidance for evacuation [2]. The literature on the use of sensor networks (WSNs)[3] and distributed systems in order to guide evacuees during an emergency is abundant, but such systems require a viable infrastructure for sensing the hazards, identifying evacuees and communicating with them, and finding safe paths. Thus this paper studies the use of widely available and lightweight wearable opportunistic network nodes that can be special purpose devices, or smart phones and personal digital assistants.

Based on the above, the prior research can be grouped into two areas. Papers from the first depend on the existence of a sensor network for emergency navigation. For example, a distributed navigation algorithm, which implemented and evaluated on a physical sensor network introduced by Li et al.[4]. This solution relies on the flooding model (in which each sensor exchanges information with every other sensor), therefore, this solution does not scale well, due to a very high communication cost. A distributed navigation algorithm, which based on the temporally ordered routing algorithm (TORA), is also proposed in [5] in order to guide civilians in a building with a 2D layout, and in [6] the solution is extended to 3D environments. Moreover, there are some works where the congestion in crowds have taken into account, such as in [7], [8], and a solution where rescue force flexibility is also examined is introduced in [7].

Solutions[9] from the second group are essentially disparate from the first, since data is disseminated by opportunistic communications formed by mobile communication nodes (CNs), and each CN exchanges emergency messages (EMs) over an opportunistic network (oppnet) that operates as part of the Emergency Support System (ESS). Furthermore, each civilian is guided by his/her own CN, which locally calculates the best evacuation path based on the gathered EMs. SNs in the ESS [9] we describe do not form a conventional wireless sensor network, since EMs are not disseminated among them (because the limited energy and physical capabilities of SNs and the possibility of the damage caused by catastrophic events), instead CNs form a network in an opportunistic manner as devices come into contact. Thus, SNs (having short range wireless communication) in our system are only utilized for civilian localization, i.e. to tell the portable CNs about the location of the mobile user in the building, as in an indoor environment GPS localization is not reliable, and to monitor the environment.

Thus, this paper provides an enhanced path finding algorithm to guide evacuees from the hazardous areas to safe exits in a direction that avoids hazards and a communication protocol to reduce the number of the unnecessarily sent EMs. Directions, which are the main part of the algorithms, are estimated for each evacuee from the current position of all the evacuees based on Opportunistic Communications (oppcomms) information sharing. We present experimental results based on simulations with the DBES tool [10], showing the degree of improvement that the directional path finding algorithm and the enhanced communication protocol can offer compared to previous approaches.

2. The Novel Algorithms

The main element of our novel algorithms (a path finding algorithm and a communication protocol) is: always to maintain the directions from hazardous areas (i.e. fire areas) to the exits. With the help of these directions our navigation system can guide the civilians not through the shortest path but through a safer one. Once a SN detects hazards in its local environment, it generates a new emergency message (EM) that includes the location of the hazard and its intensity, the device ID and the observation timestamp and forwards to CNs in communication range. Each EM is identified by its (device ID, timestamp) pair. CNs use oppcomms to disseminate EMs to other CNs. From the received EMs a CN can update its own local graph (which are stored on the device) and calculates a path to the determined exit.

2.1.The Direction Based Path Finding Algorithm

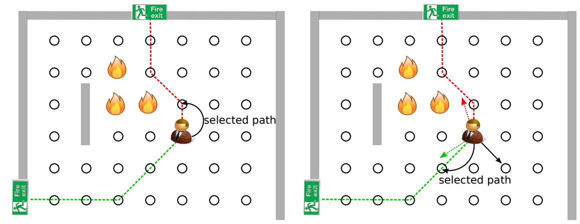
A simple evacuation example is depicted in Figure 1. In this case, there are two exits having unique evacuation paths (indicated by red and green). With the Dijkstra's shortest path algorithm the civilian will choose the "red" path, since it is shorter than the "green" path (shown in Figure 1(a)). However, this is the shortest path, but it leads the civilian towards hazardous areas which can be very dangerous. Thus, it would be beneficial if the path finding algorithm can somehow lead the civilian not through the shortest path, but through a safer one (even if it is longer than the others). Our idea was that we can utilize directions to predict the safety metric of a path, and based on these directions the civilian should choose the "green" path instead of the "red" one (shown in Figure 1(b)).

For each exit a direction vector should be calculated, which describes the main orientation of the evacuation path belongs to this exit. Thus, this direction points from the civilian current position to the selected exit. Another vector should be determined as well, which is the optimal evacuation direction from the hazardous area. This vector (called fire vector) points from the hazardous area to the civilian position. These vectors are depicted in Figure 1(b). The vectors indicated by red and green belong to the exits, while the "black" one is the so called fire vector. The proposed algorithm depends on these directions to guide the civilian through a safe path to a fire exit.

In the first phase, our algorithm calculates the aforementioned vectors. Exit vectors are easy to calculate, since each CN (which is carried by a civilian) can obtain its location from the fixed sensor nodes and the layout of the given area is available on the CN, thus the positions of the exits are also accessible for each civilian. The determination of the fire vector is a bit more sophisticated, since the location and the intensity of the hazard are included in EMs, and a CN could have many messages. Therefore, the algorithm should aggregate all the information contained by the gathered EMs. Since EMs also include their creation date, they can be easily ordered chronologically. And based on this order the first message (the most recent one) is the most relevant, as it contains the newest state of the environment, therefore, the locations in the messages should be weighted by factoring in their creation time. Thus, the resultant vector could be calculated as follows:

$$\vec{v}_{sum} = \sum_{j=t_0}^{tn-1} \frac{1}{2^{<j>}} \vec{v}_j \tag{1}$$

In Equation (1) there are n different EMs (identified by (device ID, timestamp) pair), v_{t_i} is a direction



(a) Based on the shortest path the civilian will choose the "red" path

(b) By using directions, our algorithm can guide the civilian through the safer "green" path.

Figure 1. An evacuation example.

vector (therefore, the result does not depend on the distance between the civilian and the hazardous area) carried by the EM (from the affected location to the current civilian's position) generated at t_i and $< j >$ equals to i *iff.* $j = t_i$. It is easy to see, that when $n \rightarrow \infty$ then the newest message has the same weight as all the preceding weights aggregated.

Based on the previously calculated vectors, the algorithm attempts to find the safest path, thus the next step is the calculation of the novel cost function. A CN could have many exit vectors, but only one fire vector (as it is a resultant vector determined from the received EMs), therefore, the angle between a fire vector and an exit vector can be calculated simply. Relying on these angles it could be drawn, that paths with smaller angle (angle between the selected exit vector and the fire vector) are more likely to be safer than the paths with higher ones (as it could be seen in Figure 1(b)). Hence, the novel cost function could be defined as follows:

$$\hat{F}(i, G) \equiv \hat{F}_i = \frac{-cos(\phi_i) + 1}{2} * D_i \qquad (2)$$

Where ϕ_i denotes the aforementioned angle, D_i is the shortest path cost to the i^{th} exit and G is the layout of the area.

However, the cost function defined in Equation (2) seems appropriate for selecting safe paths, it contains an error. Lets assume there are two exits, one right next to the civilian's position while the other is actually very far from the source, and the first exit's angle (ϕ_i) is much bigger than the other's. In this case the algorithm with this cost function will choose the further exit but the optimal choice would be the closer one. To prevent this, the cost function should be modified with a new factor:

$$\rho_i = \frac{\Delta_i}{min_i D_i} * \hat{F}_i \qquad (3)$$

ρ_i is called uncertainty factor, and its purpose is to reduce the probability of choosing a suboptimal path based on the directions. Δ_i is the difference between the shortest path's cost to the ith exit and the minimum of the shortest path's costs to each exit ($\Delta_i = D_i - min_i D_i$). Thus, the final version of the cost function is the sum of the previous cost function and the uncertainty factor.

$$F(i, G) \equiv F_i = \hat{F}_i + \rho_i = \frac{(-cos(\phi_i) + 1) * D_i^2}{2 * min_i D_i} \qquad (4)$$

Our novel path finding algorithm uses the previously presented cost function (Equation (4)) to select the most appropriate evacuation path. Every time a CN receives a new EM, it recalculates the exit and the fire vectors, and based on the vectors it updates the cost of each path. This method ensures, that the civilian will be guided toward the most appropriate fire exit.

2.2.Directional Extension of Epidemic Routing

Most data forwarding and routing protocols for opportunistic networks [11] attempt to find a balance between message delivery ratio and resource consumption [12], [13]. For the dissemination of EMs, which are very short in nature, a high delivery ratio and low message latencies are crucial. A fine example of opportunistic communication protocols is the Epidemic Routing protocol [14], which disseminates multiple copies of a message over the network similar to the spread of an infectious disease. The main idea behind the use of the Epidemic Routing protocol was that each EM is intended for all CNs in the system.

Since with our novel path finding algorithm CNs are not interested in all EMs, only the ones that can change the evacuation path, we can limit the number of disseminated EMs. There are two reasons that an EM can change the path:

- it contains novel intensity information, thus the weights in the graph (and D_i as well) will be modified;
- it contains novel hazardous areas, thus it changes the fire vector (ϕ_i will be modified in the cost function).

In our case, when the path finding algorithm uses directions to select the optimal evacuation path, the effect of the first reason is less important than the second. From the Equation (1) it could be seen that the resultant fire vector contains all the vectors in the received EMs but with exponentially decreasing weights. Thus, an EM with lower timestamp (which means it is created earlier) can only modify the resultant vector negligible, therefore, there is no need to transfer this message. Furthermore, a threshold (α_t) can be determined whether a newly received message can significantly modify the resultant vector or not. This threshold depends on the location of the exit, the layout of the area and many other factors. Therefore, an appropriate threshold should be given for each scenario individually.

The basis of the presented novel protocol is the Epidemic Routing protocol [14], but only those messages will be exchanged among the nodes, which (a) are created later than the receiver's latest message timestamp; and (b) which determine a new direction (if $\vec{v}_{sum} * \vec{v}_{sum'} < cos(\alpha_t)$) for the evacuation path.

It is important to note, that the proposed protocol can only be used together with our novel path finding protocol, since it exploits directions in the EM to decide whether it should be transmitted.

3. Performance through Simulation

We have chosen to conduct a simulation study using the DBES tool [10] in a realistic evacuation scenario. In order to compare with earlier results, we use the same parameter values as in [9].

A real-life example of a shopping centre (the layout was created from the blueprint of a real shopping centre in London) is used in the simulations. The layout contains 8 fire exits and 321 other movement nodes, where each node (i.e. graph vertex) has a maximum capacity (in our case it is set to 10). Thus, when a graph vertex has more civilians than its maximum capacity, that node becomes overcrowded and the simulations take physical congestion into account. The number of customers in a shopping centre may vary in a wide range (depending on the day, offers, holidays, etc.), thus four different civilian densities (400 which is a sparse presence, 600 and 800 are intermediate cases and 1000 civilians which would be fairly crowded) are examined during the simulations.

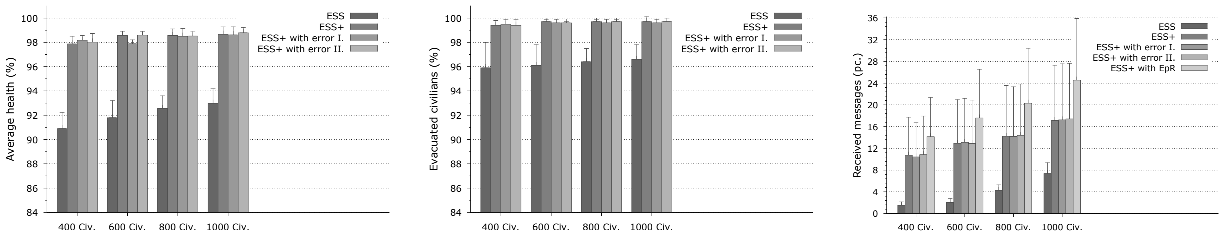
Another very important parameter is the starting position of the fire hazard: we have chosen a critical location which is very close to 3 exits (because in other cases the shortest evacuation path to the nearest exit could be a good (but definitely not the best) solution as well, as the evacuation path from the hazardous area to the nearest exit is much less likely on the path of the fire, since the fire is being spread from a centre node towards the exits), so the fire will spread very quickly towards the exits and then these exits become unreachable.

In this paper, we mainly focus on the success of the evacuation procedure by measuring the state of the evacuees themselves, while many works of emergency management with sensor networks focus on the technical aspects of the network itself (such as the communication system efficiency, the packet travel delays, and the security [15], [16]).

Simulation results will be shown regarding two different aspects (the first aspect highlights the differences between the path finding algorithms, while the second set of results focuses on the success of the communication protocol):

- The first is the main focus of the paper, and it relates to the ultimate success of the evacuation. We measure how many evacuees reach the exit in how much time during the evacuation, and also evaluate their health level when they do exit the system. The percentage indicated is a measure of the effectiveness of the emergency evacuation system, and it captures the primary security metric of the proposed system;
- The second aspect focuses on the mobile self-organized network, and it measures the number of messages that are exchanged between CNs. This is a performance indicator of the communication protocol that is being used.

Results from the first aspect are shown in Figure 2(a) and 2(b). Four different systems were used during the simulations. The first one (indicated with ESS label) represents the same emergency system as in [9]. In this case the Dijkstra's shortest path algorithm is used together with the original version of Epidemic Routing protocol in order to rescue as many civilians as possible. The second, third and fourth are the enhanced emergency support systems that work with our novel path finding algorithm and communication protocol. They only differ in the error model being used for the localization. ESS+ is an ideal scenario with no error in the positioning system, therefore, each SN can tell the exact position of a CN. Since this is



(a) Average evacuee health vs. number of the civilians.

(b) Evacuated civilians vs. number of the civilians.

(c) Received messages vs. number of the civilians.

Figure 2. Results of the evacuation. In each group the first column (ESS) indicates the same emergency system as proposed in [9]. The second one (ESS+) is the enhanced system but without any localization error (an ideal case). The third and fourth are the enhanced version as well, but with localization noise (which follows the normal distribution with maximum of 2 and 10 m). The fifth (in (c) subfigure), indicating the enhanced ESS with Epidemic Routing protocol.

not a real-life assumption, a Gaussian error model with the maximum error set to 2m (I) and 10m (II) was introduced into the system. When observing the number of the evacuated civilians (depicted in Figure 2(b)) it could be seen that ESS achieves around 95%–96%, which means that in the most dense case 950–960 civilians can be evacuated, but unfortunately the other 40–50 were unable to reach the exits in time, while ESS+ can overperform this with about 3%–4%, which improvement means 30–40 people in the overcrowded scenario. The average health levels (expressed as a percentage) of the successfully exited (thus, if a civilian could not exit the building, his/her health is not taken into account) evacuees are shown in Figure 2(a). In this performance indicator the differences between the normal and the enhanced emergency system are even more, around 6%–7%. That means the extended system does not only rescue more people from the building, but the evacuated civilians have better health as well. Moreover, the results indicate that the proposed path finding algorithm is tolerant to positioning errors, since the variants of ESS+ achieve nearly the same results with differences well within statistical variations due to the simulations.

One important thing should be noticed, namely that the ESS (and other systems as well) gives better results when the density of the civilians is higher (so the performance of the ESS is dependent on population density). This could be counterintuitive, since more crowded infrastructures usually result in more damaging evacuation plans, however, in our case, there was no fire alarm, thus, civilians start the evacuation process at different times, which eases congestion during evacuation and, on the other hand, this is the positive impact of the self-organized mobile networks formed by the CNs: more nodes mean better communication opportunities, therefore, EMs can be delivered faster and more reliably to all CNs.

Our final results relate to the mobile self-organized network formed by the CNs. The average numbers of the successfully received EMs are depicted in Figure 2(c). When examining this aspect a new system (the fifth column in each group) is need to be introduced, which is the enhanced ESS (ESS+) but implemented with the Epidemic Routing protocol, since with ESS the nodes are forming different networks than with ESS+ (because CNs are moving through different paths). And to draw the right conclusions the same networks and the same conditions should be established. Thus, in this aspect the first column is meaningless, it is depicted only for completeness. From the results it could be said, that our protocol can achieve much better results than the Epidemic Routing protocol, when the number of duplications is taken into account. This is the positive impact of the transmission mechanism (where α_t has been chosen to $\pi/4$) defined in section 2.2. Thus, only those messages will be exchanged among the CNs which fulfil the two requirements (the first relates to the creation date, while the second depends on the contained fire vector). It could be seen as well, that increasing the density of the civilians, the number of the transferred EMs is increasing as well. This is axiomatic, since the average size of the network formed by the CNs is bigger as well.

4. Conclusions

The autonomous ESS (presented in [9]) was extended with a novel path finding algorithm and a communication protocol. The main idea behind the algorithms was the same: utilize directions in order to achieve better results. The path finding algorithm uses directions (such as fire and exit vectors) to search for a safe path to a nearby exit, while the communication protocol is an enhanced version of the Epidemic Routing protocol.

A single-story building (that was created from the blueprint of a real shopping centre in London) with fire hazard and four different civilian densities was used as a case study to evaluate how our novel algorithms can improve the performance of the emergency support system. The experimental results show that an emergency support system extended with these algorithms can offer significant improvements for the evacuees (when the health and the number of the evacuated civilian are taken into account), and can also reduce the resource consumption in the mobile self-organized network.

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