Intelligent Navigation Systems for Building Evacuation

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Abstract. Intelligent navigation systems can significantly improve the evacuation of civilians in urban emergencies by providing dynamic directions to the evacuees as the hazard spreads. In this paper, we propose two distributed and adaptive systems for building evacuation. The first system, called *intelligent evacuation system (IES)*, is composed of a wireless network of static decision nodes (DNs) installed in the building which provide movement decision support to evacuees by directing them to exits via less hazardous routes. The second system, called *opportunistic communications based evacuation system (OCES)*, is based on mobile communication nodes (CNs) carried by civilians, which form an opportunistic network to exchange information on the situation and provide directions to civilians. We evaluate our systems' performance with simulation experiments of a three-floor office building. Our results indicate that both systems can greatly improve the outcome of an emergency.

Keywords: Building evacuation, intelligent systems, opportunistic communications, emergency navigation.

1 Introduction

To address the issues of safe and quick evacuation of buildings under dynamic conditions, we propose the use of emergency evacuation systems which use sensing and communications to safely evacuate people when some major hazard, such as fire or explosion, is detected. We specifically propose two different evacuation systems and provide simulation results to show that significant improvements can be obtained through their use. In this paper, we evaluate the IES and OCES as separate systems: only one of them would be installed in the building for evacuation support at any time.

2 Description of Proposed Systems

We assume that the building is represented as a graph $G(V, E)$. Vertices V are locations where civilians can congregate, such as rooms, corridors and doorways, and edges E are physical paths that can be taken by the civilians for movement. Edges have multiple costs: edge length $l(i, j)$, which is the physical distance between vertices $i, j \in V$, $h(i, j)$, which is the hazard intensity along this edge, and $L(i, j) = l(i, j) \cdot h(i, j)$, which is the "effective" edge length, a joint metric combining physical distance and hazard for shortest path calculations. Note that $h(i, j) = 1$ when there is no hazard on the edge and its value increases with the value of the observed hazard.

We also assume that the building graph is known for a building. Both the IES and OCES are supported by fixed **sensor nodes (SNs)** installed in the building, where each SN monitors a graph edge. Each SN has a unique device ID, a location tag that corresponds to the area (i.e. edge) it monitors, and very short-range (1m–2m) wireless communication capability so it can relay its measurements to other entities in the system, such as DNs in the IES and CNs in the OCES. We assume that SNs are very simple, battery-operated devices, with little to no generic computing power, low memory capacity and restricted energy constraints. Because of these limitations, SNs *do not* perform any data storage, processing or decision making. Each measurement is stored until it is over-written by a newer measurement. When a DN or CN requests the current measurement from an SN, the SN sends its $h(i, j)$ value to the requester.

2.1 Intelligent Evacuation System

Our proposed intelligent evacuation system (IES) [3] consists of static **decision nodes (DNs)**, which are installed at specific locations inside the building (at each graph vertex). Each DN has short-range wireless communication capability, some local processor and memory, and a dynamic visual panel to present directions to civilians. The main role of a DN is to compute the best direction towards a building exit and communicate this to the evacuees in its vicinity. Hazard information is provided to DNs by their adjacent SNs, and this information is further propagated among DNs based on the distributed decision algorithm as presented below. Each DN, positioned at vertex u, stores the following information:

- the effective edge lengths to neighbors: $L(u, n)$, $\forall n \in V \mid (u, n) \in E$
- the effective lengths of the paths to an exit for all neighbors: $L(n, e)$, $\forall n \in V \mid (u, n) \in E$ and e is a building exit,
- the effective length of the shortest path (SP) from u to an exit e: $L(u, e)$,
- the next suggested DN d (i.e. the next hop along the SP from u to an exit).

The distributed decision algorithm, given in Alg. 1, is executed periodically by each DN and updates both the executing DN's neighbors (i.e. their $L(n, e)$ values) and the DN itself (its $L(u, n)$, $L(u, e)$ and d values). Note that $L(u, n)$ values are updated based on measurements received from the SNs. The algorithm is based on principles developed in [5,7], and inspired by the distributed shortest path algorithm [8] and adaptive routing techniques such as the Cognitive Packet Network [6]. Its output is the next hop (i.e. DN) along the SP to the nearest building exit. As edge costs are a combination of physical distance and hazard

Algorithm 1 Distributed decision algorithm for the IES. A DN updates its suggested direction via communication with its adjacent DNs and SNs.

```
procedure UPDATEDN(u)
    for all n ∈ V | (u, n) ∈ E do
        Send L(u, e) to n
        Get h(u, n) from SN for (u, n)
        L(u, n) ← l(u, n) · h(u, n)
    end for
    L(u, e) = min{L(u, n) + L(n, e), ∀n ∈ V | (u, n) ∈ E}
    d = argmin{L(u, n) + L(n, e), ∀n ∈ V | (u, n) ∈ E}
end procedure
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intensity, the IES directs the civilians towards the exits while avoiding dangerous areas in the building. Prior to executing the algorithm for the first time, exit DNs set their $L(u, e)$ values to 0, while all other DNs set it to ∞. Note that since DNs only use local information, the IES is a distributed system that does not require global information.

2.2 Opportunistic Communications based Evacuation System

The opportunistic communications based evacuation system (OCES) is composed of **mobile communication nodes (CNs)** carried by civilians. In the OCES, we assume that each civilian is equipped with a pocket- or hand-held device, with storage and processing capacity that would be equivalent to a mobile phone or similar unit, capable of short range (up to 10m) wireless communication. CNs form a network in an opportunistic manner as devices come into contact as a result of the vicinity of other humans and their mobility. Opportunistic communications (oppcomms) are characterized by the "store-carry-forward" paradigm [9] where CNs carry messages in local storage and then forward it to others when they get in communication range. Thus, a message is delivered to its destination via successive opportunistic contacts. Because the opportunistic network (oppnet) can be disconnected for long periods of time, CNs may need to carry messages for long durations and delivery of messages is not guaranteed.

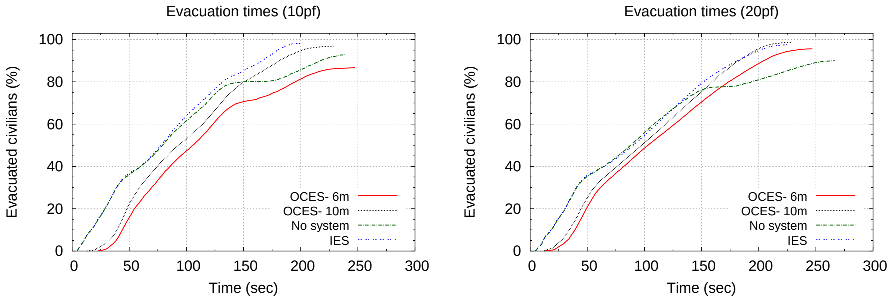
Oppcomms are used to disseminate **emergency messages (EMs)** containing information on the hazard (i.e. location and intensity) among CNs. A CN obtains hazard observations from SNs in its vicinity, which are then translated by the CN into EMs that include the CN ID, locations (e.g. edges), intensities and timestamps of the hazard observation(s). An EM is disseminated among all CNs in the OCES, meaning each EM is sent network-wide. The first hazard observation or EM received by a CN acts as an alarm, indicating that there is a hazard and the civilian should evacuate the building. Each received EM is used to update the edge costs stored locally by a receiving CN, and triggers re-calculation of its local evacuation SP. The evacuation SP from the current CN location to the nearest building exit is calculated using Dijkstra's SP algorithm. Since effective edge lengths ($L(i, j)$ values) are used in SP calculation, the "shortest" path minimizes exposure to the hazard while also minimizing travel distance.

A CN uses its evacuation SP to provide a navigation service to its civilian by guiding her towards the next hop (i.e. graph vertex) on the SP. CNs use the SNs to find their location in the building. CNs request the location tag from their nearby SNs as they move within the building, and each near-by SN sends back a **localization message (LM)** which contains its location (or the monitored area, i.e. edge). CNs can then find out where they are in the building based on these LMs. The actual position of a CN is therefore approximated by its inferred location (vertex) on the building graph. **Epidemic routing (ER)** [11] is used for the dissemination of EMs in the oppnet. We have found that ER is very suitable for the OCES due to its flooding-based approach which closely matches how EMs should be disseminated, and its high message delivery ratio and low message latencies [10], which are critical in emergency communications. In order to store EMs, CNs employ *timestamp-priority queues*, where EMs with the earliest creation timestamps are dropped from the queue when it is full.

3 Experimental Evaluation

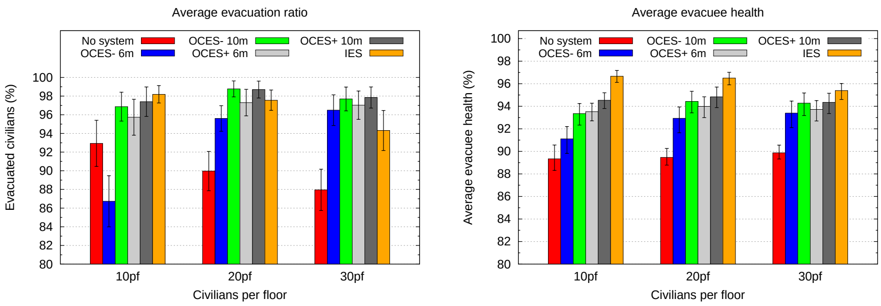
We have evaluated the IES and OCES with simulation experiments in the case of a fire in a three-floor office building using the distributed building evacuation simulator (DBES) [1], which is a multi-agent discrete-event simulation platform that can be coupled with real-life networks, such as WSNs [4]. The two building exits are located on the ground floor. Before a civilian is notified of the fire, she follows a probabilistic mobility model which simulates inter-office movement. After being alerted of the fire, civilians follow directions provided by the IES or the OCES. We assume that in the IES experiments the execution period of the distributed decision algorithm is 100ms. All communication entities are assumed to have wireless capabilities similar to IEEE 802.15.4-2006. We also assume that entities on different floors cannot communicate. Each data point in the presented results is an average of 50 simulation runs; each run represents a different distribution of civilians over all vertices of the building. The spread pattern for the fire is based on a probabilistic model inspired by [2]. Where appropriate, experimental results are presented with their 95% confidence intervals. In all experiments the fire starts at time 0 at the intersection of two corridors (near the staircases) on the 2nd floor.

We compare our proposed systems under different scenarios: (i) In the **IES with alarm (IES)** scenario, all civilians are alerted of the fire via a central alarm as soon as the fire starts and they then follow dynamic directions provided by the DNs to evacuate the building. (ii) In the **OCES without alarm (OCES$^-$)** scenario, we assume that there is *no central alarm* in the building, so civilians are alerted and guided only by the OCES. (iii) The **OCES with alarm (OCES$^+$)** scenario assumes a central alarm as in the IES scenario, but civilians are guided by the OCES. (iv) The **no system (NoSys)** scenario simulates the case where there is no evacuation support system in the building other than a fire alarm.



(a) 10pf (b) 20pf

Fig. 1. Ratio of evacuated civilians vs. simulation time, for 10 and 20 civilians per floor.



(a) Evacuation ratio (b) Evacuee health

Fig. 2. Ratio of evacuated civilians and average evacuee health vs. population density.

Figure 1a shows that OCES$^-$ performs worse than NoSys when population density and CN communication range are both low. In this case, CNs are disconnected from the rest of the oppnet for a considerable amount of time, which means that civilians are alerted late of the fire and do not receive up-to-date evacuation guidance as the fire spreads. However, OCES$^-$ performance improves with a longer communication range (i.e. 10m) and surpasses NoSys in terms of evacuated civilians even with a low population density. In the 10pf case, the IES performs the best in terms of both evacuated civilians and evacuation time. With a higher population density (20pf), OCES$^-$ performance improves and as population density and communication range increase, OCES$^-$ performs better than IES. This is due to increased connectivity in the oppnet with increasing density and range, while IES performance gets slightly worse with increasing density due to physical congestion during evacuation (e.g. at the staircases). OCES$^-$ is not affected by congestion as much since civilians start evacuating at different times due to the lack of a central alarm. In Fig. 2, trends similar to the above discussion are observed. The effect of the central alarm in $OCES^+$ (compared to $OCES^-$) is most apparent at low population densities (10pf), and the alarm loses its effectiveness as OCES performance improves with increasing density and/or communication range.

4 Conclusions and Future Work

We have proposed and described two intelligent navigation systems for building evacuation in cases of dynamic hazards such as a fire. We have evaluated our systems using simulation experiments of a three-floor building in case of a fire. Our results indicate that IES provides a good overall performance, while OCES performs poorly in low population densities when a short communication range is used but surpasses IES in denser populations or with higher communication ranges. In future work, we aim to investigate how IES and OCES can be deployed simultaneously to improve evacuation, for example when there are failures in the system.

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