Autonomous Navigation Systems for Emergency Management in Buildings

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***Abstract*—The evacuation of urban areas during an emergency is complex and challenging due to the dynamic conditions and ambiguity of information available to people in the affected area. Autonomous navigation systems can improve the outcome of such evacuations by providing up-to-date guidance and directions to people during the emergency. In this paper we present two distributed navigation systems deployed inside a confined space, such as a building, that use simple but effective communications to gather and disseminate information for the computation of evacuation paths. The first system is composed of a network of static decision nodes (DNs) positioned in the building, where DNs distributedly compute the best paths using local communication and computation, and each DN provides directions to people in its vicinity. The second system is composed of mobile communication nodes (CNs) carried by the people in the area. CNs form an opportunistic network in order to exchange information regarding the hazard and each CNs directs its user towards the safest/closest exit. Sensor nodes pre-deployed in the building monitor the environment and provide their measurements to both systems. We investigate the effect of failures of DNs on the evacuation outcome and study how the two systems can be used in conjunction to overcome such problems. A multi-agent simulation platform is used for the performance evaluation of our proposed systems in evacuation scenarios inside a three-floor building.**

***Keywords*-Adaptive navigation systems; opportunistic communications; emergency simulation;building evacuation.**

I. Introduction

In urban emergencies, people in the affected area and others that may be heading towards the area need to be informed of the situation and evacuated quickly and safely to minimize the risk of casualties. Such evacuations can be complex and challenging due to the dynamic nature of the situation. People would have to quickly decide on a safe path to an exit, which can be difficult without accurate information regarding the hazard or prior knowledge of the area [1]. Furthermore, the best paths may rapidly change as the hazard spreads and crowds block certain choke-points. Autonomous systems that monitor the environment and provide up-to-date evacuation directions to civilians as the emergency evolves can greatly improve the outcome of these evacuations.

In this paper we propose two autonomous navigation systems to provide evacuation guidance to people in confined spaces, such as buildings. Both systems employ simple but effective wireless communications in order to gather information on the current situation and calculate the evacuation paths. The first system is based on static nodes that use local communications and computation to distributedly calculate paths, whereas the second system is based on mobile nodes that employ opportunistic communications. Our approach is inspired by the autonomic systems presented in [2], [3] where a QoS-driven network system called the Cognitive Packet Network (CPN) is used to provide best-effort QoS to users. CPN selects network paths based on user-defined QoS criteria such as packet delay and loss. In the context of navigating people, we can derive direct analogies between concepts from CPN and our proposed systems here. For example, packets travelling in a CPN network can be thought of as civilians moving in the building; packet delay becomes physical travel time of civilians and packet loss is fatally injured people. We look at how failures in the fixed infrastructure of our proposed systems affect QoS and investigate how the evacuation procedure can be enhanced by the joint use of the proposed systems.

II. Related Work

There has been various approaches to the problem of providing navigation services during emergencies, most of them using a wireless sensor network (WSN) to both monitor the environment and calculate the paths. Initial work in this area includes [4] and [5], where distributed algorithms for robot navigation using WSNs are presented. These works generally include a small number of sensors and static hazard locations. Similar work by Li et al. [6] describes a distributed algorithm to guide objects through a 2D region with static danger locations using a WSN. Their approach is based on artificial potential fields and robotics motion planning. Tseng et al. [7] propose a distributed navigation algorithm based on the temporally ordered routing algorithm (TORA) for mobile ad hoc networks in order to guide civilians in a building during an emergency. They introduce the concept of "hazard regions" around danger locations but still use fixed hazard zones in their experiments. Their algorithm calculates paths that try to avoid the hazard regions as much as possible, but their evaluations do not include any actual users in the system. [8] extend the work in [9] to 3D indoor building environments by adding stairway nodes to connect different floors. Barnes et al. [10] present a distributed WSN-based building evacuation algorithm that takes into account the expected spread of the hazard inside the building. Works by Li et al. [11] and Willigen et al. [12] consider congestion during evacuation in their proposed distributed evacuation methods where they use WSNs as the navigation infrastructure. [11] additionally investigates how the WSN can be used to guide rescuers to critical areas in the building to reduce congestion and save trapped civilians. [13] presents an autonomous indoor navigation system based on mobile phones. They assume a WSN to monitor the building and receive updates on a dynamic hazard, and this information is fed into a centralized emergency guidance system to compute evacuation paths for civilians. Path information is relayed to civilians via their Internet-connected mobile phones. Wireless beacon devices pre-installed in the building are used to locate civilians, who carry a small beacon receiver in addition to their smartphones for location tracking.

III. Description of the Navigation Systems

The design of our autonomous navigation systems is closely related to the nature of the operational environment. Here, we describe our systems as deployed in multi-floor buildings. We assume that the building is represented as a graph $G(V,E)$, where vertices V are locations where civilians can congregate, such as rooms, corridors and doorways, and edges E are physical paths that civilians can take to move. The length $l(i,j)$ of an edge is the physical distance between vertices $i,j \in V$ while $h(i,j)$ represents the hazard intensity along this edge. We also define the "effective" length $L(i,j)$ of an edge as $L(i,j) = l(i,j) \cdot h(i,j)$. This metric expresses how hazardous an edge is for a civilian. When there is no hazard along the edge, $L \equiv l$. As the value of h increases, the corresponding edge becomes more hazardous to traverse. An example of the graph representation of a building floor can be seen in Fig. 3. We also assume that there are **sensor nodes (SNs)** installed in the building, where each SN monitors a graph edge as depicted in Fig. 1. Each SN has a unique device ID, a location tag that corresponds to the area (i.e. edge) it monitors, and short-range (~2m) wireless communication capability so it can relay its measurements to other entities in the system, such as DNs and CNs. We assume that SNs are simple devices with low computing power and memory capacity. When a DN or CN requests the current measurement from an SN, the SN sends it its $h(i,j)$ value.

A. Intelligent Evacuation System

Our proposed intelligent evacuation system (IES) [14] 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. 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).

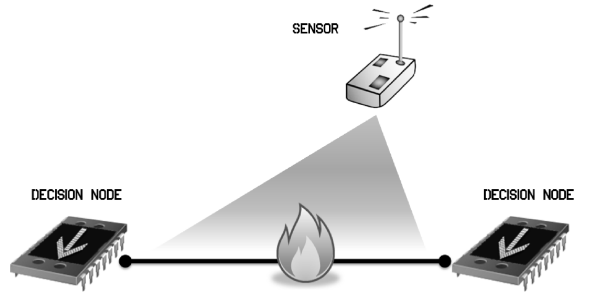


Figure 1. A sensor node (SN) monitors a graph edge for possible hazards. In the IES, decision nodes (DNs) located at graph vertices receive measurements from their adjacent SNs and provide dynamic directions during evacuation. In addition to receiving sensor measurements from SNs in communication range, the mobile communication nodes (CNs) of the OCES use the SNs for localization.

The distributed decision algorithm, given in Alg. 1, is executed periodically by each DN and updates both the executing DN's neighbors and the DN itself. The algorithm is based on principles developed in [15], [16], and inspired by the distributed shortest path algorithm [17] and adaptive routing techniques such as the Cognitive Packet Network [2]. 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 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.

B. Opportunistic Communications based Evacuation System

The opportunistic communications based evacuation system (OCES) [18] 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

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 $n \in V \mid (u,n) \in E$ **do**
  Send $L(u,e)$ to n
  Get $h(u,n)$ from SN for (u,n)
  $L(u,n) \leftarrow l(u,n) \cdot h(u,n)$
 end for
 $L(u,e) = min\{L(u,n) + L(n,e), \forall n \in V \mid (u,n) \in E\}$
 $d = argmin\{L(u,n) + L(n,e), \forall n \in V \mid (u,n) \in E\}$
end procedure

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 [19] 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.

Each CN stores the building graph and related edge costs. Oppcomms are used to disseminate *emergency messages (EMs)* containing information on the hazard (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. A CN communicates directions to its user via audio-visual signals. Each received EM is used to update the edge costs stored locally by a receiving CN, and triggers re-calculation of its evacuation path. The evacuation path from the current CN location to the nearest building exit is calculated using Dijkstra's shortest path (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 SN within communication range 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 and their movement history. The actual position of a CN is therefore approximated by its inferred location (vertex) on the building graph. *Epidemic routing (ER)* [20] 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 [21], 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.

IV. Evaluation of the Navigation Systems

We have implemented our proposed navigation systems using the Distributed Building Evacuation Simulator (DBES) [22]. The DBES is an agent-based discrete-event simulation platform for the simulation of emergency scenarios in confined and outdoor urban areas. Each actor (e.g. civilian, computing device, emergency response personnel, etc.) is represented as an agent with its own behaviour models (e.g. health and movement models for civilians). The physical environment (e.g. the building) is represented as a graph in the DBES as described in Sec. III. All data points in the presented results are the average of 50 simulation runs. For each simulation run, the initial locations of people in the simulated building are chosen from a uniform distribution over the respective graph vertices within each floor to help evaluation of system performance in different occupancy patterns. We also change the spreading pattern and rate of the hazard (i.e. fire) in each simulation run, which is based on the probabilistic hazard model in the simulations [23], [24].

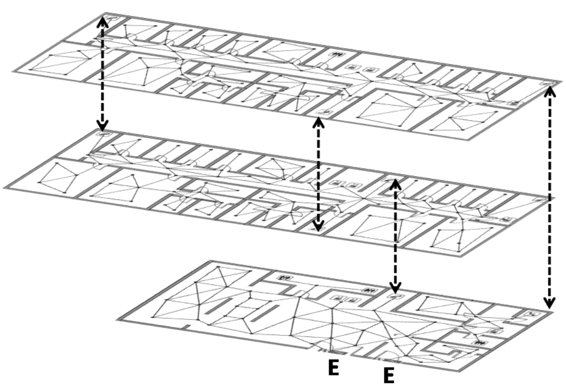


Figure 2. The three-storey building used in simulation experiments, depicting the stairways and building exits.

We simulate evacuation scenarios of the three-floor office building (24m x 60m) depicted in Fig 2, where the three

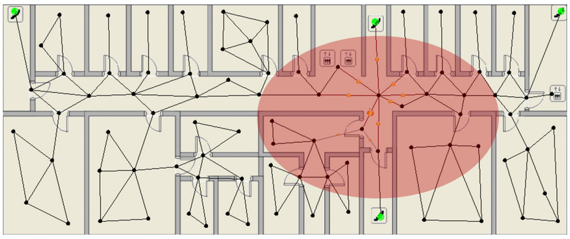


Figure 3. Fire damages part of the DN infrastructure

floors are connected by three staircases, one at each end of the floors and one in the middle. The two exits are located on the ground floor. A fire erupts in the 2nd floor, near the middle staircase, which triggers the evacuation procedure. We look at two building occupancy levels: 30 civilians (10 per floor) and 60 civilians (20 per floor). In some of the scenarios we will assume that some of the DN infrastructure used by the IES is destroyed around the initial fire location, as depicted in Fig. 3. The DNs located inside the highlighted area stop functioning and do not report updates regarding their effective length value. As a result, the IES has to use obsolete information when calculating the best paths towards an exit. This has a negative effect on the performance of the IES and on the overall outcome of the evacuation procedure, as we will see in Sec. IV-B. We then look at how the joint use of IES and OCES can improve evacuation outcome in cases of DN failures.

A. Simulation Scenarios

The "No System" scenario is an optimistic benchmark where no navigation system is used during evacuation. It is a best-case scenario since each evacuee is assumed to be familiar with the building (i.e. they know the whole building graph) and is able to calculate and follow the shortest path that leads to an exit. In this scenario, all civilians start to evacuate as soon as the fire starts. An evacuee becomes aware of a hazardous location when she reaches a location close to an area affected by the fire. This triggers an update in her knowledge of the building graph and a re-calculation of her shortest path. In the "IES" scenario, evacuation starts as soon as the fire starts and the IES is used by the people in the building, where each civilian follows directions given to her by the nearest DN. Each DN executes the distributed algorithm every 100ms. In the "IES + Failures" scenario, part of the DNs are damaged by the fire (see Fig. 3). The affected DNs stop functioning, do not execute the distributed algorithm and do not communicate with their neighbour DNs. A way to overcome the DN failures is investigated in the "IES + OCES + Failures" scenario. In this case we use the OCES as a backup system; when a failure occurs in the IES, it informs evacuees to switch to using their CNs in order to get evacuation directions. After this point, all evacuees are given directions by the CNs they carry. The communication range of each CN is set to 8m in these simulations.

B. Simulation Results

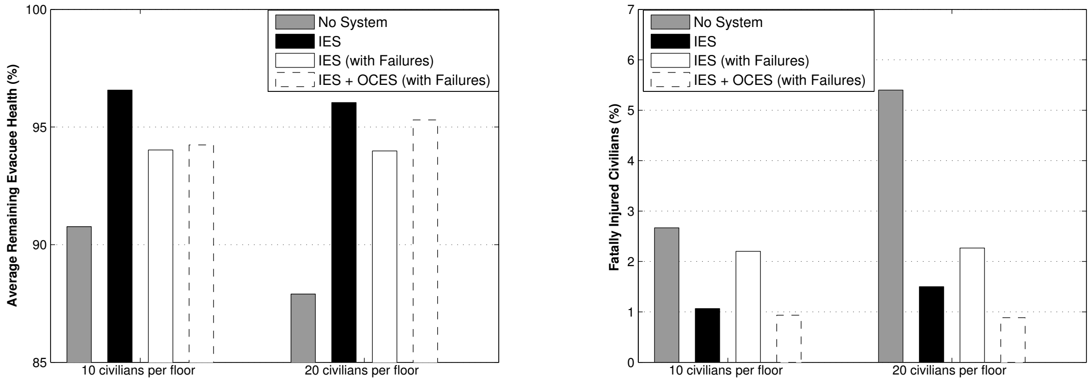
Figure 4 depicts the average evacuee health (for all successfully evacuated civilians) and the ratio of fatally injured civilians to all civilians, for all four simulation scenarios. We observe that the case with no system operating in the building exhibits the worst performance. This an expected outcome, since in this case the occupants of the building do not have knowledge of where the hazard is and how it spreads (until they encounter it) and, consequently, some of the evacuation paths initially calculated by the people will not be safe. Because people learn of the hazard only when they encounter it, they sustain more injuries (due to exposure to the fire). This causes a decrease in the average number and health of successfully evacuated people. When the IES is in use the evacuation outcome is improved since the system guides evacuees along paths that minimize exposure to the hazard. This is verified by the higher values of average evacuee health and lower values of ratio of fatally injured civilians. DN failures, however, have a negative impact on the performance of the IES: some of the DNs need to use obsolete information regarding the hazard, and as the hazard spreads previously safe paths may become dangerous. The use of the OCES as an alternative when failures occur improves evacuation results, as we observe in Fig. 4, since the OCES does not depend on the static DNs.

The beneficial effects of using the OCES as a backup when there are DN failures can be seen more clearly in Fig. 5, which better shows the evacuation process itself. It can be seen that when there are DN failures, although the evacuation time of the last survivor is significantly higher in the "IES + OCES + Failures" scenario than others, the use of the OCES improves both the number and health of evacuated civilians. This is because although OCES routes people through safer paths, some of the people have to back-track when they switch to the OCES, increasing evacuation time.

Finally we should highlight the effect of the population density on the performance of our navigation systems. We can observe from Figs. 4 and 5 that a more densely populated building results in higher evacuation times and a higher percentage of fatalities. This is due to increased congestion with increasing population density. As evacuees need more time to exit the building, the fire spreads in multiple locations and more paths become hazardous to traverse. We should also note how the performance of the OCES improves with increasing population sizes. This is due to the increased connectivity in the oppnet with increasing civilian density.

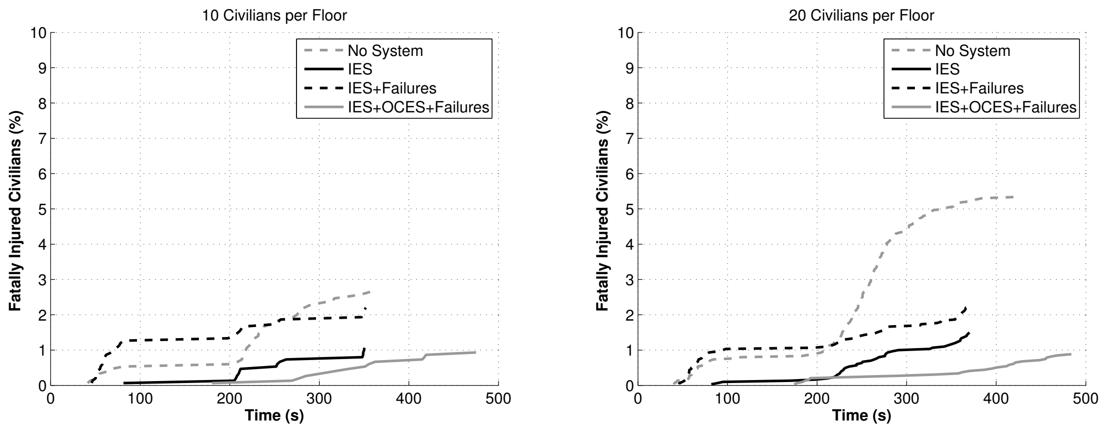
V. Conclusions and Future Work

We have proposed two autonomous navigation systems for providing evacuation guidance to people in an urban emergency and have described our systems as deployed in



(a) (b)

Figure 4. Average evacuee health (a) and average ratio of fatally injured civilians (b) for different building occupancy levels



(a) (b)

Figure 5. Ratio of fatally injured civilians vs. evacuation time, for different building occupancy levels

buildings. The first system (IES) is based on static decision nodes (DNs) that run a distributed algorithm. DNs do not use global information and communicate only with their neighbours to distributedly determine the best (i.e. safest and quickest) evacuation paths. The second system (OCES) is composed of cheap wireless communication nodes (CNs) that are carried by the civilians. The CNs form an opportunistic network which enables the exchange of emergency messages among them for alerting and guiding civilians during evacuation. Both systems are supported by pre-deployed sensors that provide real-time information on the hazard by monitoring the building. We evaluate our systems using a distributed simulation platform (DBES) using simulation scenarios of a three-storey building. We investigate how DN failures affect the evacuation outcome and demonstrate that by combining the two navigation systems we can overcome malfunctions of the DN infrastructure. In future work we will study alternative mechanisms for improving the performance of the IES when failures are present.

As we look at areas for future research, we think that mathematical modeling of emergency management systems has not been sufficiently explored, while it is a standard technique in computer system performance evaluation [25], as well as in distributed systems [26]. Another useful approach would be to evaluate the effect of uncertainty in the sources of information [27] and in their interpretation. An advantage of such approaches is that they can provide computationally fast mathematical prediction, much faster than the simulation methods described in this paper, so that the outcome of a large number of simulations can be replaced by the solution of a probability model. We think that such methods are worth investigating in view of the increasing importance of emergency management and more generally for the study of human based cyber-technical systems.

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References

[1] T. J. Shields and K. E. Boyce, "A study of evacuation from large retail stores," *Fire Safety Journal*, vol. 35, no. 1, pp. 25 – 49, 2000.

[2] E. Gelenbe, R. Lent, and Z. Xu, "Measurement and performance of a cognitive packet network," *Computer Networks*, vol. 37, no. 6, pp. 691–701, Dec. 2001.

[3] E. Gelenbe, M. Gellman, R. Lent, P. Liu, and P. Su, "Autonomous smart routing for network QoS," in *Proc. 1st Int. Conf. on Autonomic Computing*, May 2004, pp. 232–239.

[4] M. Batalin, G. S. Sukhatme, and M. Hattig, "Mobile robot navigation using a sensor network," in *IEEE Int. Conf. on Robotics and Automation*, April 2004, pp. 636–642.

[5] P. Corke, R. Peterson, and D. Rus, "Networked robots: Flying robot navigation using a sensor net," in *11th Int. Symp. of Robotics Research (ISRR 2003)*. Springer-Verlag, October 2003, pp. 234–243.

[6] Q. Li, M. D. Rosa, and D. Rus, "Distributed algorithms for guiding navigation across a sensor network," in *MobiCom '03: Proc. 9th Ann. Int. Conf. on Mobile computing and networking*. ACM, September 14-19 2003, pp. 313–325.

[7] Y.-C. Tseng, M.-S. Pan, and Y.-Y. Tsai, "Wireless sensor networks for emergency navigation," *Computer*, vol. 39, no. 7, pp. 55–62, 2006.

[8] M.-S. Pan, C.-H. Tsai, and Y.-C. Tseng, "Emergency guiding and monitoring applications in indoor 3D environments by wireless sensor networks," *Int. Journal of Sensor Networks*, vol. 1, no. 1/2, pp. 2–10, Jan. 2006.

[9] Y.-C. Tseng, M.-S. Pan, and Y.-Y. Tsai, "Wireless sensor networks for emergency navigation," *IEEE Computer*, vol. 39, no. 7, pp. 55–62, Jul. 2006.

[10] M. Barnes, H. Leather, and D. K. Arvind, "Emergency evacuation using wireless sensor networks," in *Proc. 32nd IEEE Conf. on Local Computer Networks (LCN'07)*, Oct 2007, pp. 851–857.

[11] S. Li, A. Zhan, X. Wu, and G. Chen, "ERN: Emergency rescue navigation with wireless sensor networks," in *Proc. 15th Int. Conf. on Parallel and Distributed Systems (ICPADS'09)*, Dec. 2009, pp. 361–368.

[12] W. van Willigen, R. Neef, A. van Lieburg, and M. C. Schut, "WILLEM: A wireless intelligent evacuation method," in *Proc. 3rd Int. Conf. on Sensor Technologies and Applications (SENSORCOMM'09)*, Jun. 2009, pp. 382–387.

[13] Y. Inoue, A. Sashima, T. Ikeda, and K. Kurumatani, "Indoor emergency evacuation service on autonomous navigation system using mobile phone," in *Proc. 2nd Int. Symp. on Universal Communication (ISUC'08)*, Dec. 2008, pp. 79–85.

[14] A. Filippoupolitis and E. Gelenbe, "A distributed decision support system for building evacuation," in *Proc. 2nd IEEE Int. Conf. on Human System Interaction*, May 2009, pp. 323–330.

[15] E. Gelenbe, E. Seref, and Z. Xu, "Simulation with learning agents," *Proc. of the IEEE*, vol. 89, no. 2, pp. 148–157, Feb. 2001.

[16] E. Gelenbe, "Sensible decisions based on QoS," *Computational Management Science*, vol. 1, no. 1, pp. 1–14, 2004.

[17] P. A. Humblet, "Another adaptive distributed shortest path algorithm," *IEEE Transactions on Communications*, vol. 39, no. 6, pp. 995–1003, Jun. 1991.

[18] G. Gorbil and E. Gelenbe, "Opportunistic communications for emergency support systems," in *Proc. 2nd Int. Conf. on Ambient Systems, Networks and Technologies*, Sep. 2011, to appear.

[19] L. Pelusi, A. Passarella, and M. Conti, "Opportunistic networking: Data forwarding in disconnected mobile ad hoc networks," *IEEE Communications Magazine*, vol. 44, no. 11, pp. 134–141, Nov. 2006.

[20] A. Vahdat and D. Becker, "Epidemic routing for partially-connected ad hoc networks," Duke Univ. Dept. of Computer Science, Technical Report CS-2000-06, Apr. 2000.

[21] L. Song and D. F. Kotz, "Evaluating opportunistic routing protocols with large realistic contact traces," in *Proc. 2nd ACM Workshop on Challenged Networks (CHANTS'07)*. ACM, 2007, pp. 35–42.

[22] N. Dimakis, A. Filippoupolitis, and E. Gelenbe, "Distributed building evacuation simulator for smart emergency management," *The Computer Journal*, vol. 53, no. 9, pp. 1384–1400, 2010.

[23] A. Filippoupolitis, L. Hey, G. Loukas, E. Gelenbe, and S. Timotheou, "Emergency response simulation using wireless sensor networks," in *Proc. 1st Int. Conf. on Ambient Media and Systems (Ambi-Sys'08)*. ICST, 2008, pp. 21:1–21:7.

[24] D. G. Elms, A. H. Buchanan, and J. W. Dusing, "Modeling fire spread in buildings," *Fire Technology*, vol. 20, no. 1, pp. 11–19, 1984.

[25] E. Gelenbe, "A unified approach to the evaluation of a class of replacement algorithms," *IEEE Transactions on Computers*, vol. C-22, no. 6, pp. 611–618, June 1973.

[26] E. Gelenbe and K. C. Sevcik, "Analysis of update synchronisation algorithms for multiple copy data bases," *IEEE Transactions on Computers*, vol. C-28, no. 10, pp. 737–747, October 1979.

[27] E. Gelenbe and G. Hébrail, "A probability model of uncertainty in data bases," in *ICDE*, 1986, pp. 328–333.