Tracking Evacuation of Pedestrians during Disasters

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***Abstract*—In times of natural or man-made disasters, missions such as safe evacuation of people from the disaster areas have critical importance. Considering large areas with limited vehicle use such as theme parks and state fairs, search and rescue of the pedestrians is a major challenge. Moreover, as an effect of disaster, damages to infrastructure may disrupt the use of Internet services. Therefore, alternative communication systems with disaster resilience are necessary for evacuation planning and guidance.**

In this paper, we develop a method for tracking pedestrians using smart-phones during disasters. In the network model, sensors store and carry messages to a limited number of mobile sinks. We propose *physical force based* (PF), *grid allocation based* (GA) and *road allocation based* (RA) approaches for sink placement and mobility. The proposed approaches are analyzed through extensive network simulations using real theme park maps and a theme park pedestrian mobility model for disaster scenarios.

I. INTRODUCTION

Communication networks are being used worldwide and Internet offers various services that made daily lives of people easier in many ways. However, depending only on Internet as a reliable communication source for disaster management may cause people suffer as possible infrastructure damages may disrupt the use of services. Considering vulnerabilities of the networks and Internet, researchers are nowadays focusing on development of networks resilient to disasters. The purpose of these networks is to provide and maintain acceptable level of service during natural or man-made disasters, as well as accidents or faults in infrastructure.

While disaster resilient networks is becoming increasingly popular research area, most studies focus on challenges such as the use of networks in cities effected by disasters such as earthquakes [1]. We study the use of disaster resilient networks for safe evacuation of crowds from disaster areas. We consider areas such as theme parks where the vehicle use is limited. The administrators of theme parks aim to evacuate pedestrians safely from the disaster area and rescue them when needed. Large places that restrain people from using transportation vehicles such as airports, large-scale city parks, shopping malls, fairs, and festival areas are considered in this context.

In this study, we focus on the application scenario of theme parks that are large and crowded entertainment areas. Large-scale theme parks have substantial economic contributions to their regions. While overall popularity of theme parks increases every year, global success of the growing industry is severely affected by disasters such as Hurricane Irene [2]. A natural or man-made disaster in a theme park may cause damages to regions such as Central Florida, which has theme parks with highest yearly attendances and also being known as home to natural disasters including hurricanes, floods and tornadoes.

We describe our modeling of the theme park environment as a combination of roads, obstacles and lands in Section III. We use real theme park maps for synthetic generation of the theme park models. For realistic modeling of the human mobility, we use a scenario-specific mobility model for disaster scenarios [3], [4]. In this model, we simulated the mobility of theme park visitors who aim to escape from the disaster area to the gates in order to reach transportation vehicles or ambulances. The crowd dynamics during the pedestrian flows are modeled by the social force model [5].

As a disaster response strategy, we propose the use of wireless sensor network (WSN) with mobile sinks which includes mobile sensors and a limited number of mobile sinks. Mobile phones carried by pedestrians are used as sensor devices which communicate with each other and mobile sinks. Mobile sinks monitor the evacuation process by collecting data from sensor nodes. Mobile sinks can be either robots or security personnel patrolling by walk or by electronic transportation vehicles such as Segway devices. Sensor nodes create messages when they witness effected areas or people who need immediate help. They store and carry the messages and deliver to the mobile sinks via hop-by-hop wireless communication.

Since sensor devices are carried by ordinary theme park visitors whose prior goal is escaping from the disaster area, we focus on the effective positioning and mobility of mobile sinks to gather more data from sensors and find pedestrians in need of help. For efficient tracking of the people during the evacuation, we propose three approaches in Section IV, namely, *physical force based* (PF), *grid allocation based* (GA) and *road allocation based* (RA) for mobile sink placement and mobility. PF is inspired by gravitation, in a way that sensor nodes attract mobile sinks, and mobile sinks distract each other. In GA, each sink allocates a number of grids, which are created on top of the roads, as its own operating region while in RA, each sink allocates one or multiple roads close to each other. After allocation of grids or roads, mobile sinks patrol in their allocated regions by a random movement model.

II. RELATED WORK

We previously studied the use of WSNs with mobile sinks in theme parks for the purpose of event coverage [6]. In this study, we focus on the use of mobile sinks for security in theme parks in ordinary scenario of daily theme park operation.

There are many research studies for solving the emergency evacuation problem in city environments such as downtown areas and evacuation of buildings during disasters. Park et al. [7] propose a rule based approach to model spontaneous evacuation behavior considering a terrorist attack scenario in a complex metropolitan area. Chen and Zhan [8] compare the simultaneous and staged evacuation strategies. In the simultaneous strategy, the city residents evacuate simultaneously, whereas in the staged strategy, residents in different areas of the city evacuate according to different sequences of the zones within the area. They used an agent-based approach to model and simulate the traffic flows of the vehicles.

Georgoudas et al. [9] propose an anticipative system to avoid congestions at the exit points while the pedestrians are evacuating. Fujihara and Miwa [1] investigate the effects of opportunistic communications in evacuation times for disaster scenarios. El-Sergany et al. [10] propose a model for evacuation planning and disaster management in flood disaster scenarios. Iizuka et al. [11] propose the use of mobile devices of evacuees to form an ad hoc network and find the evacuation routes accordingly and avoid congestions. Vukadinovic et al. [12] study the mobility of theme park visitors based on GPS traces and analyze impacts of the human mobility on wireless ad hoc networking.

III. THEME PARK AND NETWORK MODEL

A. *Theme park model*

We use real theme park maps to model the theme park environment. The maps are extracted using OpenStreetMap [13]. After processing a map, the model defines a theme park as combination of *roads*, *obstacles* and *lands*. Roads contain waypoints and people and the mobile sinks are considered to move on top of the waypoints. Obstacles are either man-made or natural. Man-made obstacles include structures such as buildings and fences, while natural obstacles are lakes, rivers, trees and so on. Lands are the regions that have no obstacle or waypoint. Fig. 1 shows a processed model of the Magic Kingdom park in Disney World. In this figure, thick black lines represent the roads while the main gate is located on top as a thick and curved blue line. The obstacles are illustrated with various types of polygons.

In the pedestrian mobility model, theme park visitors can escape from the theme park by following waypoints on the roads to reach the exit gate points. The social interactions between the pedestrians cause slow-downs or delays in the movements of the crowds. Detailed information regarding the pedestrian mobility can be found in [4].

B. *Network model*

Our proposed model includes sensor nodes and limited number of mobile sinks. The network model and the routing protocol are defined as follows.

1) Sensor nodes: Sensor nodes represent mobile devices carried by theme park visitors. The sensing of an "event", can be automatically done by the devices or messages can be created by the smart-phone users. Marking the location of a person in need of help is an example of an event. Whenever an event is sensed, the sensor node prepares a message including location and the sensing time and stores the message in its buffer. The sensor node then carries data and sends the messages on its buffer to other sensor nodes or to a mobile sink via wireless communication. Sensor nodes are assumed to have limited capabilities in terms of energy, storage, and transmission power.

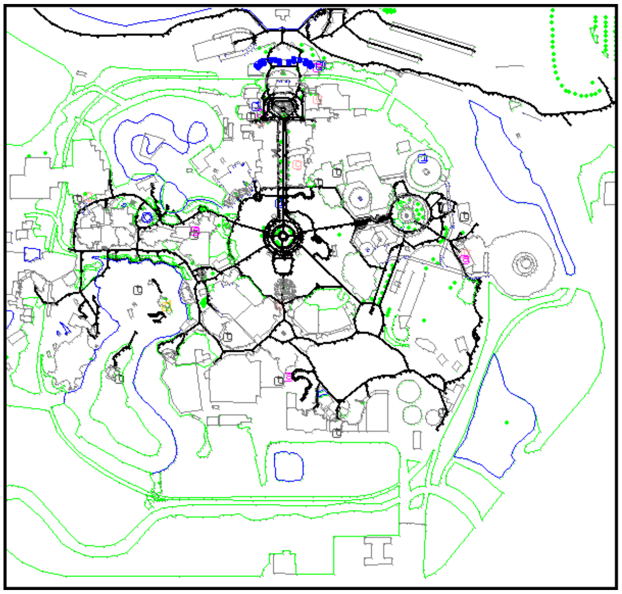

Fig. 1. The model of the Magic Kingdom park.

2) Mobile sinks: Mobile sink nodes represent either moving robots or security personnel carrying mobile devices. A security personnel can be using an electronic transportation device if available with a tablet computer attached to it. The mobile sinks patrol in the theme park and collect data from the sensor nodes. They move to the region of the event when they receive a message with a new and not responded event. Mobile sink nodes are more powerful devices with enhanced computation and communication capabilities, storage and energy resources, while they exist in limited numbers.

3) Routing Protocol: The message delivery to mobile sinks is done via hop-by-hop wireless transmissions. We use the epidemic routing protocol [14] with minor modifications regarding to the purpose of our model. Epidemic routing protocol is mainly developed for mobile wireless networks considering missions such as disaster recovery or military deployment. In epidemic routing, whenever a pair of nodes come up being in the transmission range of each other, one of them acts as the initiator and the other acts as replier. In the first phase, the initiator initiates a message transfer session by sending a summary vector of *Message IDs* located in its buffer. In the second phase, the replier compares its own vector and the received (initiator's) vector, then requests messages by sending the difference vector, which is the vector of *Message IDs* of messages that do not exist in its buffer. In the last phase, initiator sends the messages missing in replier's buffer and finishes the session.

Let us describe the aforementioned minor modifications of the epidemic routing protocol. In the epidemic routing, every node can act as either initiator or replier in a session. In our network model, however, sensors can act as either initiator

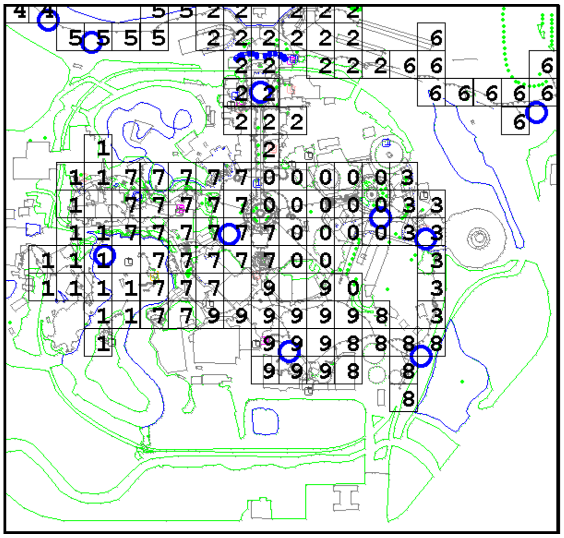

Fig. 2. Grid allocation based placement of 10 mobile sinks.

or replier while mobile sinks always act as repliers, since they have the goal of gathering data from sensors. Moreover, after a pair of sensor nodes successfully finish a session, they wait for a specific time period before initiating a new session. The time can be specified empirically and according to the density of the sensor nodes and their current speeds. For instance, if sensors stuck and wait in a road for long time due to high crowd densities, the time period can be adjusted in order to prevent unnecessary energy consumption of the message transfers.

IV. SINK PLACEMENT AND MOBILITY

A. *Initial placement*

Let us first describe the initial placement process of the mobile sinks. The process starts with creating a grid layout on the theme park model. The grids are specified with relatively small sizes (e.g., 50x50m). The small-sized grids are located only on top of the roads. In other words, obstacles and lands are excluded during the process of grid creation. Grid creation starts with generating 2D quasi-random points. Number of the generated points is equal to the number of mobile sinks. This generation is repeated iteratively and at each iteration, the sum of pairwise distances between the random points are computed. We keep the set of quasi-random points with the highest distance sum. Since this computation is done offline before the start of the operation of mobile sinks, the iteration can be repeated many times in order to have the best result.

The best set of quasi-random points are marked as the *base points*. For each grid, the closest base point is selected and the grid is marked with the index of the closest base point. Fig. 2 illustrates creation of the grids on the roads, which are assigned with 10 base points. The creation of grids and the assignment is the base for initial mobile sink distribution. Mobile sinks are represented as the blue ring-shaped nodes. As shown in Fig. 2, each mobile sink is placed on a random point, which is one of the waypoints in the grids with corresponding index. The main purpose is to distribute the sinks in a way that they share the workload while they are all located on top of the roads to start their patrolling duty.

B. *Sink mobility*

Let us now describe the mobility approaches for the mobile sinks.

1) Physical force based sink mobility (PF): In PF, the main goal of the sink mobility is tracking people and following them along during the evacuation process. Inspired by Newton's law of universal gravitation, each pedestrian assumed to have a unit mass which attracts the mobile sinks, while distances cause less attractions. A mobile sink which detected a group of people tends to follow them as long as it does not encounter with a larger group or other mobile sinks on the way. In order to prevent mobile sinks to intercept, the mobile sinks also have mass which is larger than the unit mass and they cause inverse forces in the opposite direction. The sink mass is equal to the division of the number of active pedestrians by the number of mobile sinks. Each mobile sink computes a physical force vector based on the positions of people and other mobile sinks and moves along the direction of the physical force vector. Fig. 3 illustrates the movement direction of the $Sink\ A$ after encountering with pedestrians P_1 and P_2 with unit masses and $Sink\ B$ with a higher mass producing the strongest physical force among the three forces $\vec{F_1}, \vec{F_2}$ and $\vec{F_B}$. In this case, $Sink\ A$ moves in the direction of the vector $\vec{V_A}$, which is the sum of the three physical force vectors.

Having n pedestrians and m mobile sinks with masses 1 and M respectively, the physical force movement vector $\vec{V_a}$ on the $Sink\ A$ is calculated as follows:

$$\vec{V_a} = \alpha \cdot \left(\sum_{i=1}^{n} \vec{F_i} - \sum_{j=1}^{m} \vec{F'}_j \right) \quad s.t.\ \ j \neq a \tag{1}$$

where

$$\left| \vec{F_i} \right| = G \cdot \frac{M \cdot 1}{d^2}, \tag{2}$$

$$\left| \vec{F'}_j \right| = \lambda \cdot G \cdot \frac{M \cdot M}{d^2}. \tag{3}$$

λ is an empirical constant value, which defines the impact of sink mass $M = \frac{n}{m}$ and the gravity constant G. α is the constant which adjusts the magnitude of the sum vector $\vec{V_a}$. The value of n changes during the operation according to current number of people in the theme park. Overall computational complexity for each mobile sink is $O(n+m)$. For simplicity, this computation can be done by mobile sink only considering the pedestrians and the mobile sinks in its visible area by ignoring other masses which have longer distances (d) that cause negligible forces.

2) Grid allocation based sink mobility (GA): In this approach, each mobile sink allocates a set of grids according to the grid indices which were found in the initial phase. Basically, the grids in Fig. 2 are used for allocation such that each sink is responsible for the grids with a particular number. For instance the grids which are marked as 1 are assigned to the first mobile sink, while the grids with mark 2 are assigned to the second sink and so on. During the operation, each

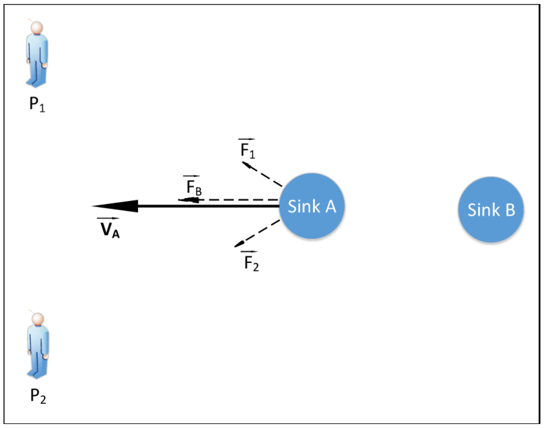

Fig. 3. The physical forces and the movement vector of $Sink\ A$ along with pedestrians P_1, P_2 and $Sink\ B$.

sink patrols in its allocated grids. The sink chooses a random waypoint as the next destination point among the waypoints of the set of allocated grids. After reaching to the next destination, the sink decides another next destination in the same fashion. This mobility model aims to divide the workload evenly on the patrolling mobile sinks, while they are not intercepting each other's region.

3) Road allocation based sink mobility (RA): In the RA approach, each sink allocates one or multiple roads. During their operation, the sinks patrol only their allocated roads. In the case of having grids with different indices on top of a same road, the number of waypoints is used for deciding which grid index is going to be used for marking the road. As in GA, the roads which are marked as 1 is assigned to the first mobile sink, and the roads with mark 2 is assigned to the second sink, and so on. The main purpose of using grid indices for road allocation is the goal of having sinks handle the closer roads instead of the sinks having roads in distant regions. Initial placement of RA is different than PF and GA, because after a mobile sink allocates roads, it chooses a random start point among the waypoints in the allocated roads. Whenever a mobile sink reaches a new destination during its operation, the mobile sink decides its next destination by choosing a random waypoint in its allocated roads.

V. SIMULATION STUDY

A. Simulation environment

In this section, we analyze the proposed models PF, GA, and RA through simulations of the WSN with mobile sinks in the Magic Kingdom park. We include two random sink mobility models for comparison, which we call "random target location" (RTL) and "random waypoint distribution" (RWD) models. In RTL, each sink chooses any random target location on the map, then sets the closest waypoint to the location as the sink's next destination. In RWD, each sink chooses a waypoint randomly among all waypoints as the next destination. RWD favors the popular roads because popular roads tend to include more waypoints than other roads.

Various metrics exist for evaluating the models and they can be classified in two types: *link-based* and *network coverage* metrics. Link-based metrics include intercontact times, recontact rate, minimum hop counts, message delays, and number of transmissions. Network coverage metrics include number of detected sensors, rescue success ratio, and average distance to detected event. We include performance results related to intercontact times, recontact rate, number of detected sensors, number of transmissions and rescue success ratio in this section.

We evaluate the success of the network with 1-10 mobile sinks and transmission ranges of 10, 20, 50 and 100m to analyze the effects of available resources. Evaluation of each setting is based on 50 simulation runs. Each simulation run generates at least about 2000 message transmissions among sensor nodes with each other or with mobile sinks. The number of transmissions to mobile sinks varies because of the sink mobility model selection and the number of mobile sinks. All nodes communicate with the epidemic routing protocol [14], while after two sensor nodes close a session, they wait for a cut off time empirically set as 1 min before opening a new session.

Table I includes the list of the simulation parameters. Parameters related to the human mobility and the social force model used in this simulation study can be found in [4]. Disasters tend to have effects on the random locations of the area during the simulation time. In the simulation study, instead of creating artificial disaster zones, we marked the pedestrians which are effected due to the effects of disasters.

TABLE I. SIMULATION PARAMETERS

simulation time	2000 s
sampling time	2.0 s
disaster area (≈)	800x800 m
number of sensor nodes	200
sensing range	20 m
sensor message storage capacity	100
transmission probability	0.9
grid width/height	50 m
number of effected people	20
rescue failure time	600 s
sink relative mass constant(λ)	0.5
physical force impact factor α	20.0
sink/pedestrian max speed	1 m/s
pedestrian visibility	50 m

B. Performance results

1) Intercontact times and recontact rates: Intercontact time is defined as the duration between two consecutive encounters of a mobile sink with a sensor node. We analyze intercontact times of PF, GA, RA, RTL and RWD with 5 mobile sinks placed in the theme park and 25m transmission range. The performance results of intercontact times with confidence bounds are shown in Fig. 4. The results reveal that PF and GA have shorter intercontact times while RWD has the worst performance and it causes mobile sinks to delay communicating with a previously contacted sensor node. Moreover, the intercontact times of PF seem very consistent, so that it is easy to estimate the next contact time with a previously contacted sensor node. In particular, consistency in the intercontact times would allow us to find effective methods for transmission scheduling.

Intercontact times do not include the case that a mobile sink communicates with a sensor node only once during the simulation time. Therefore, we analyze the recontact count for

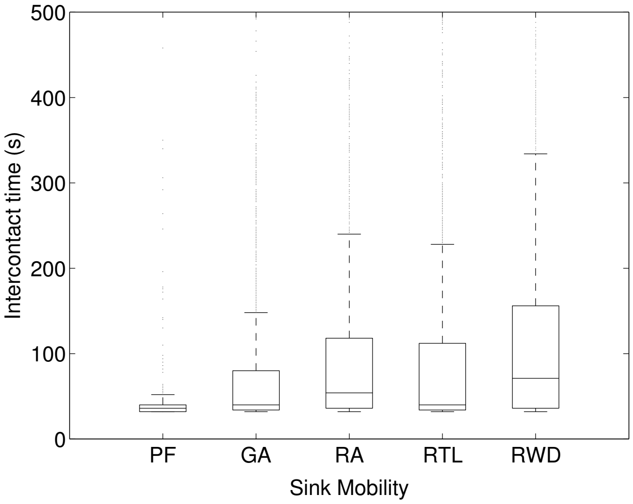

Fig. 4. Intercontact times of PF, GA, RA, RTL and RWD.

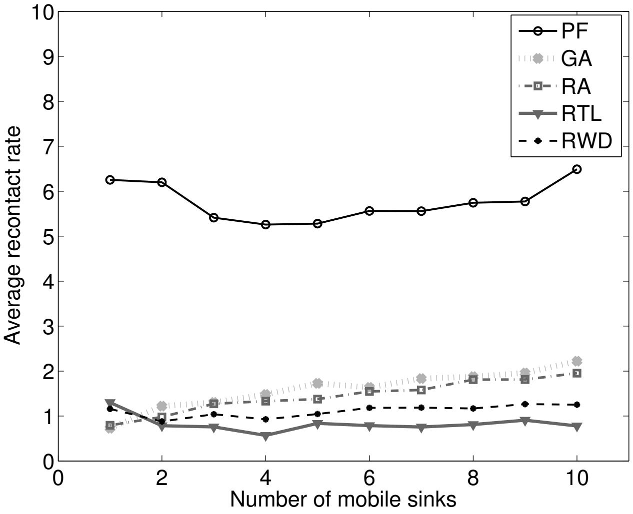

Fig. 5. Recontact rates of PF, GA, RA, RTL and RWD with 1 to 10 sinks.

each pair of sink and sensor node, which is the number of contacts of the mobile sink and the sensor node after their first communication. Recontact rate of a mobile sink is its average recontact count with all the sensor nodes. Fig. 5 shows the results of average recontact rates for settings with 1 to 10 sinks. PF is the clear winner with an average rate of more than 5.0 due to sinks' behavior of following sensor nodes and keeping in touch as much as possible. The decrease in the rates for 3 sinks is caused by the masses of other sinks which restrict them not to stay close to each other. For the setting with only 1 mobile sink, we observe that recontact rates of GA, RA, RTL and RWD are low without any significant difference between them, while the rate difference becomes significant with multiple sinks. Among these four approaches, GA is the winner reaching the rate of more than 2.0, while the rate of RA reaches approximately 2.0. On the other hand, the rates of RTL and RWD do not significantly increase with the additional number of sinks.

Considering intercontact times and recontact rates, we observe that PF is the best strategy in terms of tracking success.

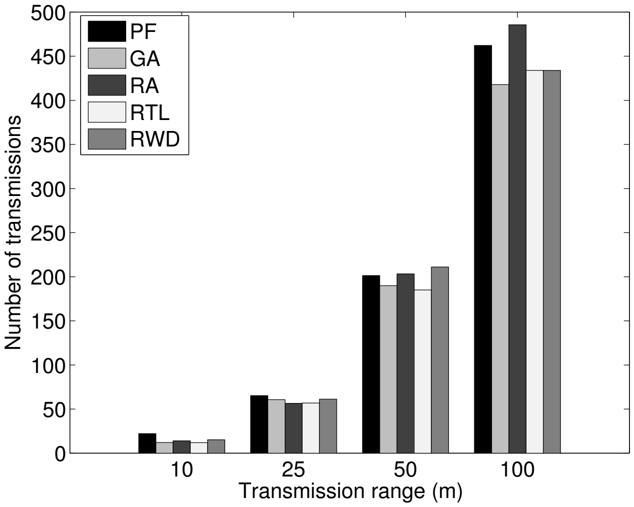

Fig. 6. Average number of transmissions of PF, GA, RA, RTL and RWD for 10m, 25m, 50m and 100m transmission ranges.

Furthermore, compared to RTL and RWD, GA and RA are better tracking strategies because of their shorter intercontact times and higher recontact rates.

2) Number of transmissions: Number of transmissions represent the energy consumption because of communication of the sensor nodes and the mobile sink nodes. We consider average number of transmissions of all nodes in the network including the transmissions in successful or failed sessions. Fig. 6 shows the results of the approaches with 5 mobile sinks for transmission ranges of 10m, 25m, 50m and 100m. First of all, the increase in transmission range dramatically increases the number of transmissions. This is an expected result caused by the exponential increase in the number of neighbors of a sensor node. In the case of having limited energy resources, a more effective routing protocol may provide better energy preservation for sensor nodes with high transmission ranges. Secondly, the use of PF results more transmissions while the difference is not very significant. This is a side effect of the PF strategy since mobile sinks are able to communicate with sensor nodes multiple times and in shorter time periods. Nonetheless, sinks are in limited number and the number of transmissions among sinks and sensor nodes is significantly less than the number of transmissions among sensor node pairs. Furthermore, sinks are assumed to have more resources in terms of energy and storage while sensor nodes which are neighbors of the sinks may consume more energy resources.

3) Number of detected sensors: We analyze the total number of detected sensors for having insight into the network's coverage performance. We assume that a sensor is detected when there is a direct communication among the sensor and any mobile sink. Fig. 7 reveals the results of the approaches for various transmission range values with 5 sinks. Among all the approaches, RA and PF are the overall winners reaching up to more than 80% of the 200 sensor nodes. RWD also provides a reasonably good coverage of sensor nodes since the mobile sinks mostly choose the popular locations where sensor nodes are also most likely present. With higher transmission ranges, the coverage performance is better for all the approaches. Having 50m or 100m transmission ranges, RA provides the

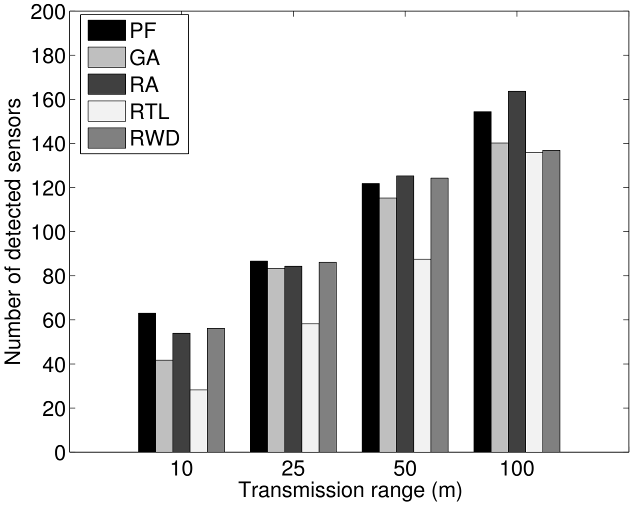

Fig. 7. Number of detected sensors of PF, GA, RA, RTL and RWD for 10m, 25m, 50m and 100m transmission ranges.

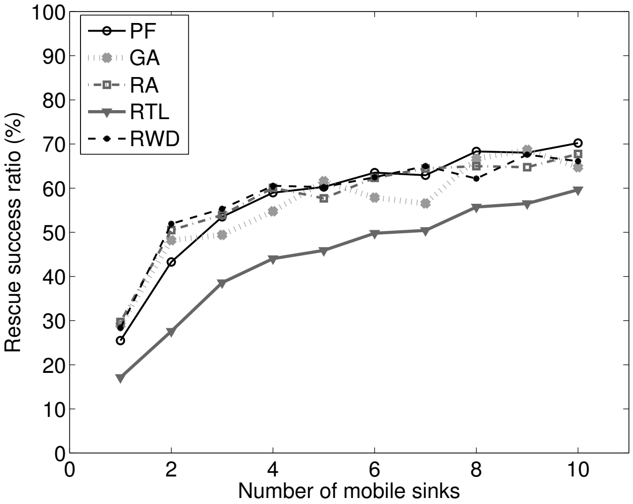

Fig. 8. Rescue success rates of PF, GA, RA, RTL and RWD with 1 to 10 mobile sinks.

best coverage such that most sensor nodes encounter with at least one mobile sink along their way.

4) Rescue success ratio: Considering mobile sinks with acting capabilities (actors), they should be able to reach the pedestrians in need of help in acceptable amounts of time. Thus, we analyze the rescue success ratios. Rescue success depends on the message delay and the time it takes for the mobile sink to move to the effected pedestrian. We assume a rescue time of 10 minutes, which includes the message delay and the travel time of the mobile sink. Fig. 8 shows the success ratio results of the approaches with 25m transmission range. This figure also reveals the effect of having multiple mobile sinks for having better rescue success ratios. With 10 mobile sinks, PF reaches more than 70% of an effected pedestrian in less than 10 minutes. For RTL, success ratio increases from 10% to 60% from 1 to 10 mobile sinks while for the other approaches it increases approximately from 30% to 70%.

Overall, the proposed approaches produce better results in terms of link-based performance, network coverage, and rescue success. PF produces the best results of intercontact times and recontact rates. RA provides the best network coverage for high transmission ranges. GA has better energy efficiency due to less number of message transmissions, while having the second-best link-based performance.

VI. CONCLUSION

In this paper, we propose the use of smart-phones and mobile sinks for tracking pedestrians during their evacuation from disasters. We consider the use of multiple mobile sinks and propose the *physical force based* (PF), *grid allocation based* (GA) and *road allocation based* (RA) approaches for sink placement and mobility. The performances of the proposed approaches as well as two random sink mobility models are evaluated through extensive network and mobility simulations for the theme park scenario. The simulation results show that the proposed approaches provide better network coverage and rescue success and do not cause extra communication overhead.

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