Short and Reliable Path Selection for Automatic Evacuation Guiding Based on Interactions between Evacuees and Their Mobile Devices

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Abstract. When large-scale disasters occur, evacuees have to evacuate to a refuge quickly. For this purpose, there has been proposed an automatic evacuation guiding scheme based on implicit interactions among evacuees, their mobile devices, and networks. In this scheme, an evacuation route is obtained as the shortest path, which may not be safe. In this paper, we propose a short and reliable path selection for existing automatic evacuation guiding, which allows evacuees to evacuate quickly while avoiding encounters with blocked road segments as much as possible. First, the proposed scheme calculates k-shortest ($k \geq 1$) paths from the current location to the destination, with the help of the existing algorithm. Then, it selects the most reliable one from the candidates by taking into account road blockage probabilities, each of which is an estimated probability that the corresponding road is blocked under a certain disaster. Through simulation experiments, we show that the proposed scheme can reduce the number of encounters with blocked road segments with an appropriate value of k, while keeping the average/maximum evacuation time compared with the shortest path selection.

Keywords: Automatic evacuation guiding, path selection, path length, path reliability, road blockage probability, k-shortest path

1 Introduction

In the 2011 Great East Japan Earthquake, both fixed and mobile communication networks have been unavailable for long time and in wide areas, due to damage of information communication infrastructures. As a result, it has been reported that there were many cases where evacuees and rescuers could not collect and distribute important information, e.g. damage information, evacuation information, and government information [16]. Evacuees quickly have to evacuate to refuges along safe routes to keep their own safety when a large-scale disaster occurs. While they can acquire static information, e.g., map and location of refuges, in usual time, they cannot grasp dynamic information, e.g., blocked road segments, until the disaster occurs.

To tackle this problem, Komatsu et al. have proposed an automatic evacuation guiding scheme based on implicit interactions between evacuees and their mobile devices [14], where communication among mobile devices is enabled by Delay Tolerant Networks (DTN) [9]. In this scheme, an application for evacuation guiding tries to navigate an evacuee by presenting his/her evacuation route as a recommended route using information shared between mobile devices and/or between mobile devices and cloud systems. When a large-scale disaster occurs, the application is activated automatically. Note that the application should be pre-installed into his/her mobile device in usual time. The application calculates an evacuation route from the current position to a refuge with map and location detected by Global Positioning System (GPS), and navigates the evacuee by presenting the route. In addition, the application can also grasp the actual evacuation route of the evacuee, i.e., his/her trajectory, by measuring his/her position periodically. The evacuee tries to evacuate along the recommended route. When the evacuee discovers a blocked road segment during his/her evacuation along the recommended route, he/she will take another route by his/her own judgment. As a result of tracing his/her actual evacuation route as the trajectory, the application can detect a blocked road, which makes the difference between the recommended route and the actual evacuation route. The application can automatically estimate and record this road as a blocked road segment. We can expect that the evacuation route can be improved by sharing blocked road segments, which were discovered, when a mobile device can communicate with other mobile devices and/or the remaining communication infrastructures.

In [14], the effectiveness of the automatic evacuation guidance scheme has been evaluated in terms of the average/maximum evacuation time and the ratio of evacuees that have finished evacuating to all evacuees. They, however, do not take into account the safety of evacuation routes and the shortest path is used for the recommended route. In case of earthquakes, an evacuee has to evacuate quickly and safely by avoiding encounters with blocked road segments as much as possible. Recently, we can obtain information to predict such occurrence of blocked road segments, i.e., road blockage probability, from a certain municipality, e.g., Nagoya city in Japan [6]. (See the details in Section 4.1). In this paper, we propose a short and reliable path selection for the automatic evacuation guiding by using the information about map and road blockage probabilities. Through simulation experiments, we show the validity of the proposed scheme in terms of the total number of encounters with blocked road segments and the average/maximum evacuation time.

The rest of this paper is organized as follows. Section 2 gives related work. In Section 3, we explain the existing automatic evacuation guiding scheme. In Section 4, the proposed scheme is presented, and Section 5 gives simulation results. Finally, Section 6 provides conclusions and future work.

2 Related Work

There are several existing studies on evacuation guiding supported by information and communication technology (ICT) [10, 12, 14]. Iizuka et al. propose an evacuation guiding scheme which presents evacuees evacuation paths and evacuation timing to avoid traffic jams, by using an ad-hoc network [12]. Fujihara and Miwa propose an evacuation guiding scheme using DTN under the situations of damage to communication infrastructures [10]. Komatsu et al. propose an automatic evacuation guiding scheme based on implicit interactions among evacuees and their mobile devices [14]. In the existing studies, the evacuation route is selected from the viewpoint of speedy evacuation, e.g., route length. In the evacuation, safety is important as well as speediness. In this paper, we propose a short and reliable path selection for the automatic evacuation guiding, which allows evacuees to evacuate quickly while avoiding encounters with blocked road segments as much as possible.

There are several existing studies on the risk analysis after a disaster occurs [4–6]. In Japan, a certain municipality, e.g., Nagoya city, has been evaluating the regional risks, road blockage probabilities, after occurrence of a large-scale disaster [6]. Church and Cova map evacuation risks on transportation networks using a spatial optimization model, called critical cluster model, in which the whole area is divided into multiple small areas and small areas with high ratio of population to exit capacity are regarded as those with high evacuation risk [5]. Since the model in [5] is only based on pre-disaster factors, i.e., population and exit capacity, Chen et al. extend this model by adding post-disaster factors, e.g., spatial impact of disaster and potential traffic congestion caused by evacuation guiding. In this paper, we improve the safety of evacuation guiding by taking into account a pre-disaster factor, i.e., road blockage probability.

The concept of path reliability, which will be explained in Section 4.2, is inspired by road network reliability [1, 3, 11]. There are two kinds of definitions of road network reliability: connectivity reliability and travel time reliability [11]. Connectivity reliability is defined as a probability that there exists at least one route between the source and the destination without heavy delay or road disruption. Travel time reliability is defined as a probability that traffic on the path can reach the destination within a specified time. Iida proposes a method to analyze and to evaluate the connectivity reliability, the travel time reliability, and the reliability of the links composing the road network [11]. Chen et al. analyze a road network with traffic demands by considering the connectivity reliability, the travel time reliability, and the capacity reliability [3]. Ahuja et al. propose a method to calculate the path reliability from the reliability of each link of the path [1].

When a disaster occurs, the road network might not be able to function as usual. Thus, evacuees have to select appropriate evacuation routes by taking into account various aspects: estimated evacuation time, traveling distance, and traffic congestion. There are several studies on a multi-objective path selection [15, 17, 19]. In [19], Yuan and Wang propose path selection models for emergency logistics management, with the help of an ant colony optimization algorithm [8], in order to select a route that minimizes both total travel time and route complexity. In [15], Lu et al. assume that the available capacities of nodes and edges of the road network may change during evacuation. They model the node capacities and edge capacities as time-series data and propose capacity constrained routing algorithms. Mohammad et al. propose path selection for evacuation planning with the help of a multi-objective evolutionary algorithm, where multiple factors, i.e. the distance from refuges, the capacity of refuges, and the population, are considered [17]. In this paper, we also tackle a kind of the multi-objective path selection, which considers the path length and path reliability.

3 Automatic Evacuation Guiding Scheme

Since the proposed path selection relies on the automatic evacuation guiding scheme [14], we first introduce the overview of that scheme.

3.1 Preliminaries

$G = (\mathcal{V}, \mathcal{E})$ denotes a graph representing the internal structure of target region, where $\mathcal{V}$ is a set of vertices, i.e., intersections, and $\mathcal{E}$ is a set of edges, i.e., roads, in the map. There are N ($N > 0$) evacuees in the region and each of them has a mobile device. $\mathcal{N} = \{1, 2, \ldots, N\}$ denotes a set of the evacuees (devices). Each device $n \in \mathcal{N}$ measures and records its own locations by using GPS at intervals of I_M ($I_M > 0$) just after a disaster occurs.

3.2 Overview

Fig. 1 illustrates the flow of guiding evacuee $n \in \mathcal{N}$ to a refuge. Evacuee n has pre-installed an application for evacuation guiding into his/her mobile device before a disaster occurs. The application can obtain static information, i.e., the peripheral map of target region and the location information of refuges, in advance. When a disaster occurs, the application is initiated automatically. The application first finds out nearest refuge $d \in \mathcal{V}$ from location $s \in \mathcal{V}$ of evacuee n. Next, it calculates evacuation route $\widehat{p}_{s,d}$ and presents him/her the route as the recommended route (Step 1 in Fig. 1). Recommended route $\widehat{p}_{s,d}$ between source s and destination d on map G is given by a vector of edges constructing the route.

Evacuee n tries to move along recommended route $\widehat{p}_{s,d}$. When evacuee n discovers a blocked road segment during his/her evacuation along recommended route $\widehat{p}_{s,d}$ (Step 2 in Fig. 1), he/she will take another route by his/her own judgment (Step 3 in Fig. 1). The application can trace the actual evacuation route as a trajectory by measuring his/her positions periodically, i.e., at the interval of I_{M}. As a result, the application can detect blocked road segment $e \in \mathcal{E}$, which makes the difference between the recommended route and the actual evacuation route. Then, the application automatically records blocked

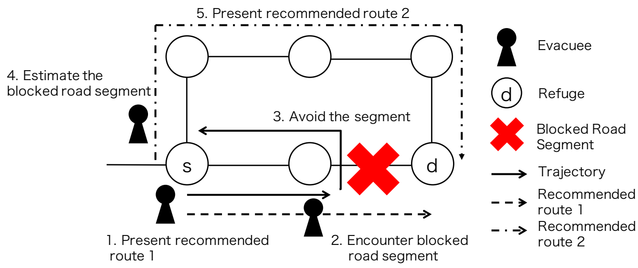


Fig. 1. Flow of evacuation guiding.

road segment e into a set of blocked road segments, $\mathcal{E}_{NG}^{n}$ (Step 4 in Fig. 1). The application further recalculates a new evacuation route $\widehat{p}_{s',d}$, which does not include blocked road segments in $\mathcal{E}_{NG}^{n}$ ($\forall e \in \mathcal{E}_{NG}^{n}$), and presents him/her the route, from current location s' to nearest refuge d (Step 5 in Fig. 1).

Evacuation guiding finishes when the evacuee reaches the refuge or the application cannot find out any evacuation route to the refuge. In addition to such self-discovery of blocked road segments, the application can also obtain new information about blocked road segments when the mobile device can communicate with other mobile devices and/or the remaining communication infrastructures. The obtained information about blocked road segments is used for route recalculation if the current recommended route contains the blocked road segments which were newly discovered. Thus, we can expect that such information sharing will improve the evacuation guiding and result in shortening evacuation time.

4 Proposed Scheme

In [14], the shortest path is applied as the recommended route for quick evacuation. In case of an earthquake, a main shock and the succeeding aftershocks might make some road segments blocked, due to secondary disasters, e.g., collapse of buildings along the route and fires. Thus, it is also important to achieve safe evacuation by avoiding encounters with such blocked road segments as much as possible. In this paper, we first model reliability of a path according to road blockage probabilities of road segments that compose the path, and propose a scheme to select a short and reliable evacuation path by taking into account the length and reliability of paths.

4.1 Road Blockage Probability

In Japan, a municipality, e.g., Nagoya city, has been evaluating the regional risks, e.g., road blockage probabilities, caused by future large-scale disasters such as Nankai Trough Earthquake [6]. The road blockage probability is an estimated probability that the corresponding road is blocked due to collapse of buildings along the road under a certain disaster. It is calculated based on the degree of collapse and height of each building along the road, and the width of the road.

4.2 Path Reliability

We define path reliability based on the road blockage probabilities. Let p_e $(0 \leq p_e \leq 1)$ denote the road blockage probability that road $e \in r$ on path r is blocked. Then, $1 - p_e$ is the probability of road availability, indicating that road e is not blocked but passable. Path availability can also be defined as the probability that all roads $\forall e \in r$ on path r are passable. If road blockage probabilities are independent, path availability is given by the product of road availability probabilities of all roads of the path, $\prod_{e \in r}(1 - p_e)$. The path availability takes a value in the range of $[0, 1]$ and a large (resp. small) value means high (resp. low) availability.

Since the existing shortest-path algorithm, e.g., Dijkstra's algorithm [7], assumes that each road has a cost and that the sum of the road costs composing a path represents the cost of the path, we additionally define path reliability by modifying the path availability as follows:

$$f_p(r) = -\sum_{e \in r} \log(1 - p_e). \tag{1}$$

Note that the path reliability becomes high (resp. low) if $f_p(r)$ is small (resp. large). When a path includes at least one road segment with a high road blockage probability, (1) takes a remarkably high value. Thus, selecting a path according to (1) will enable evacuees to avoid blocked road segments as much as possible.

4.3 Path Selection

The length of path r, i.e., path length, is given by the sum of the length of all roads composing path r:

$$f_d(r) = \sum_{e \in r} d_e, \tag{2}$$

where d_e denotes the length of road $e \in E$. First, mobile device $n \in \mathcal{N}$ calculates candidates of the recommended routes as a set of k-shortest paths, $\mathcal{P}_{s,d}^{n,k}$ $(k \geq 1)$, from current location $s \in \mathcal{V}$ to destination $d \in \mathcal{V}$. To enumerate the k-shortest paths, we can use existing algorithms, e.g., Yen's algorithm [18] and Pruned Landmark Labeling based approach [2]. Next, mobile device n selects recommended route $\widehat{p}_{s,d}^{n}$ with minimum path reliability $f_p(r)$,

$$\widehat{p}_{s,d}^{n} = \arg\min_{r \in \mathcal{P}_{s,d}^{n,k}} f_p(r). \tag{3}$$

Note that we can control the trade-off between speediness and reliability of evacuation by changing k. The proposed scheme with $k = 1$ is equivalent to the shortest path selection, while that with $k = \infty$ selects a path only based on path reliability.

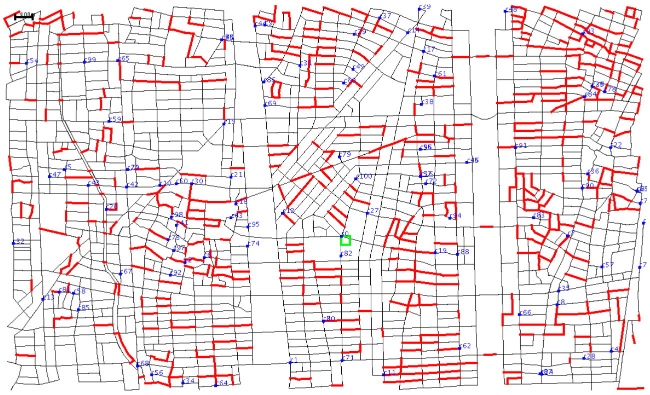


Fig. 2. Simulation area: $3,700$ [m] $\times$ $2,200$ [m] southwest area of Nagoya station in Japan.

5 Simulation Results

Through simulation experiments, we evaluate the effectiveness of the proposed scheme in terms of safety and speediness of evacuation.

5.1 Simulation Model

We used The ONE Simulator [13]. We also used the map of $3,700$ [m] $\times$ $2,200$ [m] southwest area of Nagoya station in Japan, which was provided by Nagoya city (Fig. 2). This map's internal graph structure is composed of 2,839 vertices and 5,252 directed edges. We assume a hundred evacuees with their own mobile devices. We set the simulation time to be $5,000$ [s]. When the simulation starts, a disaster occurs and the evacuees move from arbitrary points on the map (blue points in Fig. 2) to a refuge located near the center on the map (a green square in Fig. 2) at a speed of 4 [km/h].

We set measurement interval I_M to be 50 [s]. We assume communication ranges for mobile-to-mobile direct communication, e.g., Wi-Fi Direct, to be 100 [m] and communication ranges for communication with infrastructures, e.g., wireless LAN, to be 100 [m]. To focus on the effectiveness of the proposed scheme itself, we assume that mobile devices can finish retrieving information at each contact with other mobile devices and/or communication infrastructures. One wireless LAN access point (AP) is located at the refuge, and 25 AP's are placed in 5×5 grid arrangement.

As for disaster scenarios, we set the blocked road segments (red lines in Fig. 2) according to the road blockage probability of each edge on the graph. Nagoya city in Japan provides information of the road blockage probabilities for several classes depending on the degree of damages. In this paper, we use the data of maximum class that considers the possibility of all kinds of disasters. We set the

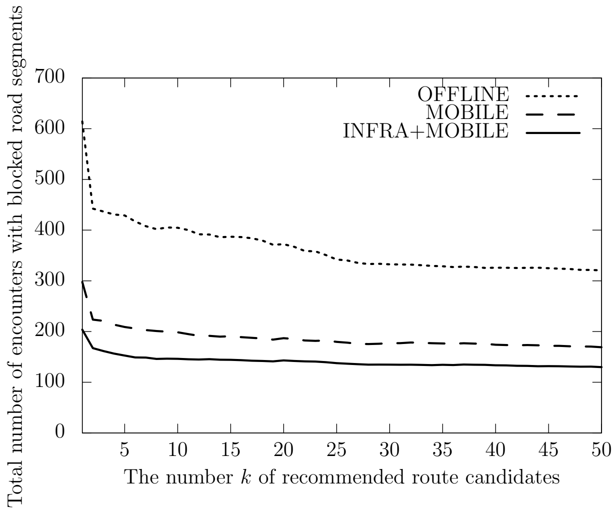


Fig. 3. Total number of encounters with blocked road segments.

number k of the recommended route candidates to be an integer value in the range of $[1, 50]$.

We use two kinds of evaluation criteria. The first one is the total number of encounters with blocked road segments of all evacuees, which is related to the safety of evacuation. The second one is the average (resp. maximum) evacuation time among evacuees, to evaluate the speediness of evacuation. Here, we define the evacuation time as the time interval from evacuation start to the evacuation completion. The succeeding results are the average of 300 independent simulation experiments.

5.2 Evacuation Movements for Evaluation

The performance of the proposed scheme is affected by communication environments. Therefore, we evaluate the following three communication environments: INFRA+MOBILE, MOBILE, and OFFLINE. In case of INFRA+MOBILE, mobile devices can communicate both with other mobile devices and with communication infrastructures. In case of MOBILE, mobile devices can communicate only with other mobile devices. In case of OFFLINE, mobile devices can communicate neither with other mobile devices nor with communication infrastructures.

In order to show the upper bound of the performance of the proposed scheme, we also evaluate ideal evacuation (IDEAL), in which all evacuees know the information about all blocked road segments before the evacuation starts.

5.3 Total Number of Encounters with Blocked Road Segments

Fig. 3 illustrates the relationship between the total number of encounters with blocked road segments of all evacuees and the number k of the recommended route candidates. First, we observe that the total number of encounters with blocked road segments monotonically decreases with k, regardless of the communication environments. This indicates that the proposed scheme can improve the safety of evacuation. We also find that the total number of encounters with blocked road segments steeply decreases when $k = 2$ and gradually decreases when $k > 3$.

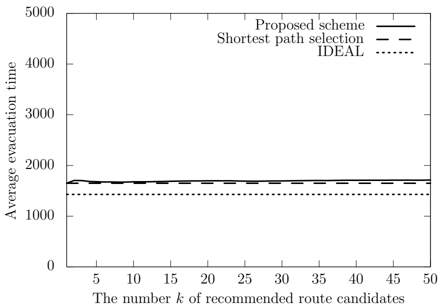
Next, we focus on the performance of the proposed scheme under each communication environment. The improvement ratio of the result of $k = 10$ (resp. $k = 50$) to that of $k = 1$ becomes 28.4%, 33.2%, and 34.0% (resp. 36.2%, 43.3%, and 47.7%) in case of INFRA+MOBILE, MOBILE, and OFFLINE, respectively. Thus, the proposed scheme is robust against inferior communication environments. In [14], the existing automatic evacuation guiding scheme tries to improve evacuation by sharing information about blocked road segments among evacuees. In addition to this mechanism, the proposed scheme also tries to guide evacuees to refuges along safe routes to avoid encounters with blocked road segments as much as possible. As a result, the proposed scheme can achieve safe evacuation even under inferior communication environments.

5.4 Evacuation Time

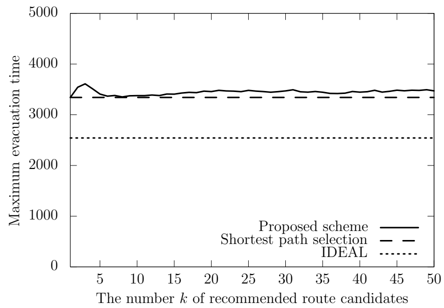
In Section 5.3, we showed that the proposed scheme with $k \geq 2$ can reduce the number of encounters with blocked road segments by selecting more reliable evacuation routes. Increase of k, however, may also make the evacuation routes longer. In this section, we evaluate the effectiveness of the proposed scheme in terms of average evacuation time and maximum evacuation time.

Figs. 4a, 4c, and 4e illustrate the transition of average evacuation time when changing k from 1 to 50 in case of INFRA+MOBILE, MOBILE, and OFFLINE, respectively. First, we focus on the impact of communication environments. We observe that INFRA+MOBILE and MOBILE show similar results while OFFLINE presents worse results than them. We also find that the proposed scheme with $k \geq 2$ can keep average evacuation time compared with that with $k = 1$, i.e., the shortest path selection, regardless of the communication environments. Specifically, the increase ratio of average evacuation time with $k \geq 2$ to that with $k = 1$ is not more than 4.8% (INFRA+MOBILE), 1.4% (MOBILE), and 1.8% (OFFLINE). This indicates that the proposed scheme can improve the safety of evacuation while keeping the average evacuation time.

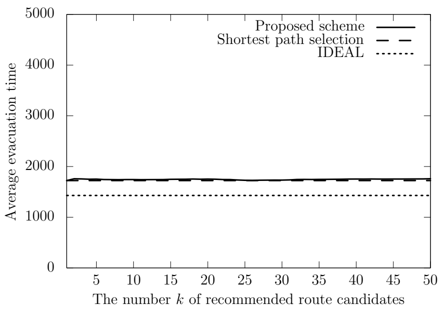
Next, Figs. 4b, 4d, and 4f illustrate the transition of maximum evacuation time when changing k from 1 to 50 in case of INFRA+MOBILE, MOBILE, and OFFLINE, respectively. We first observe that the communication environments play an important role in reducing the maximum evacuation time. Next, we focus on the performance difference among path selection schemes in each communication environment. From Figs. 4b and 4d, the proposed scheme with $k \geq 2$ in case of INFRA+MOBILE and MOBILE can also suppress the increase of the maximum evacuation time as in the case of the average evacuation time. On the contrary, in case of OFFLINE (Fig. 4f), the proposed scheme with $k \geq 2$



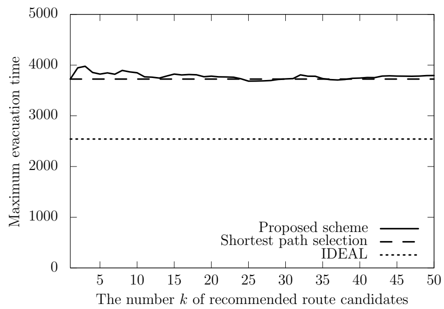
(a) Average evacuation time (INFRA+MOBILE).



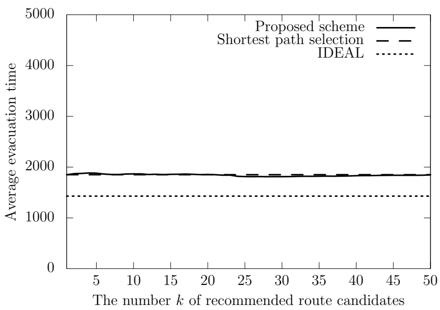
(b) Maximum evacuation time (INFRA+MOBILE).



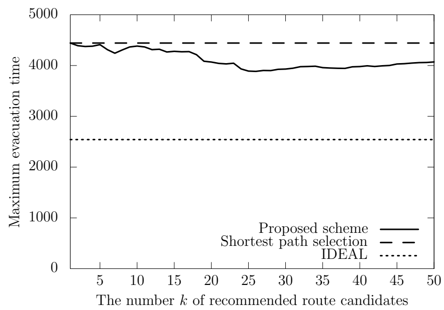
(c) Average evacuation time (MOBILE).



(d) Maximum evacuation time (MOBILE).



(e) Average evacuation time (OFFLINE).



(f) Maximum evacuation time (OFFLINE).

Fig. 4. Relationship between k and average/maximum evacuation time.

can shorten the maximum evacuation time compared with the shortest path selection. In case of OFFLINE, mobile devices cannot obtain any information from others and thus selecting reliable evacuation routes becomes more important.

5.5 Appropriate Value of the Number k of Route Candidates

From the results in Section 5.3 and Section 5.4, we find that the proposed scheme can reduce the number of encounters with blocked road segments while keeping the average/maximum evacuation time by increasing k. In our scenario, $k = 25$ seems to be an appropriate value to achieve both safe and speedy evacuation. Note that the appropriate value of k may change depending on the shape of the map and the distribution of road blockage probabilities.

6 Conclusion

When a large-scale disaster occurs, evacuees have to evacuate to the refuge quickly and safely. The existing studies, however, use the shortest path selection for speedy evacuation, and pay less attention to the safety of the evacuation route. In this paper, we first defined the path reliability based on the road blockage probability of each road segment composing the path. Next, we further proposed a short and reliable path selection. The proposed scheme first calculates k-shortest ($k \geq 1$) paths from the evacuee's current location to the destination. Next, it selects the route with the highest path reliability from the candidates.

Through simulation experiments, we showed that the proposed scheme can improve the safety of evacuation in terms of the number of encounters blocked road segments, by increasing k, regardless of the communication environments. In addition, the proposed scheme with $2 \leq k \leq 50$ can keep the average/maximum evacuation time compared with the shortest path, i.e., the proposed scheme with $k = 1$. Thus, we showed that the proposed scheme can achieve both safe and speedy evacuation. As future work, we plan to propose a scheme to determine an appropriate range of k according to the shape of the map and the distribution of road blockage probabilities.

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