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Geographical Risk Analysis Based Path Selection for Automatic, Speedy, and Reliable Evacuation Guiding Using Evacuees' Mobile Devices

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Abstract It has been highly expected to achieve speedy and reliable evacuation guiding under large scale disasters. As for the speedy evacuation, an automatic evacuation guiding scheme has been proposed, which is a reactive approach based on implicit interactions among evacuees, their mobile devices, and networks. In this scheme, an evacuation route is given by the shortest path, which may not be safe. In this paper, we propose a speedy and reliable path selection based on the geographical risk map for the existing automatic evacuation guiding, which is a proactive approach that allows evacuees to evacuate speedily while avoiding encounters with blocked road segments as much as possible. First, the proposed scheme enumerates candidates of short paths from the evacuee's current location to the refuge. 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 improve the safety of evacuation in terms of the number of encounters with blocked road segments while keeping both the average and maximum evacuation times unchanged, compared with the shortest path selection. We further demonstrate how the proactive function, i.e., geographical risk analysis, and the reactive function, i.e., information sharing, contribute to the system performance.

Keywords Geographical risk analysis · automatic evacuation guiding · path selection · path reliability

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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 (Ministry of Internal Affairs and Communications, 2011). 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 (Komatsu et al, 2018), where communication among mobile devices is enabled by Delay Tolerant Networks (DTNs) (Fall, 2003). 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 an 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.

The automatic evacuation guiding scheme is a reactive approach, which can dynamically adapt to environmental changes under disaster situations. In (Komatsu et al, 2018), 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 static information to predict occurrence of blocked road segments, i.e., road blockage probability, from a certain municipality, e.g., Nagoya city in Japan (City of Nagoya, 2015). (See the details in Section 4.1.)

In this paper, we propose a speedy and reliable path selection for the automatic evacuation guiding by using the geographical information about map and road blockage probabilities. This is a kind of proactive approach, which can be conducted before disaster occurs. We also propose a guideline of parameter determination approach for the proposed scheme to achieve both speediness and safety. 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. In particular, we expect that an evacuation guidance combining a reactive approach and a proactive approach can improve evacuation movement in enormous damage environments, e.g., inferior communication environments.

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

2.1 Evacuation Guiding Scheme

There are several existing studies on evacuation guiding supported by information and communication technology (ICT) (Fujihara and Miwa, 2014; Iizuka et al, 2011; Komatsu et al, 2018). 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 (Iizuka et al, 2011). Fujihara and Miwa propose an evacuation guiding scheme using DTN under the situations of damage to communication infrastructures (Fujihara and Miwa, 2014). It is much difficult for an evacuee to operate his/her mobile device properly even if the communication environments can be secured. In addition, evacuees may not use an evacuation guiding application and a device for the first time without understanding the operation method. Under such a background, Komatsu et al. propose an automatic evacuation guiding scheme based on implicit interactions among evacuees and their mobile devices (Komatsu et al, 2018). 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 speedy 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.

2.2 Risk Analysis

There are several existing studies on the risk analysis after a disaster occurs (Chen et al, 2012; Church and Cova, 2000; City of Nagoya, 2015; Silva et al, 2014). 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 (City of Nagoya, 2015). Silva et al. present the platform called OpenQuake engine, which is the open source software for calculating earthquake-driven risks from various viewpoints (Silva et al, 2014). The output calculated by OpenQuake engine can be used to identify vulnerable region with higher degree of damages and/or plan emergency management after a disaster occurs. 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 (Church and Cova, 2000). Since the model in (Church and Cova, 2000) 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 jams caused by evacuation guiding (Chen et al, 2012). In this paper, we improve the safety of evacuation guiding by taking into account of pre-disaster factor, i.e. road blockage probability.

2.3 Route Calculation

The concept of path reliability, which will be explained in Section 4.2, is inspired by road network reliability. (Ahuja et al, 1993; Chen et al, 2002; Iida, 1999). There are two kinds of definitions of road network reliability: connectivity reliability and travel time reliability (Iida, 1999). Connectivity reliability is defined as a probability that there exists at least one route between a source and a 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 (Iida, 1999). Chen et al. analyze a road network with traffic demands by considering the connectivity reliability, the travel time reliability, and the capacity reliability (Chen et al, 2002). Ahuja et al. propose a method to calculate the path reliability from the reliability of each link of the path (Ahuja et al, 1993).

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 of various aspects: estimated evacuation time, traveling distance, and traffic congestion. There are several studies on a multi-objective path selection (Lu et al, 2005; Mohammad et al, 2009; Yuan and Wang, 2009). In (Yuan and Wang, 2009), Yuan and Wang propose path selection models for emergency logistics management, with the help of an ant colony optimization algorithm (Dorigo et al, 2006), in order to select a route that minimizes both total travel time and route complexity. In (Lu et al, 2005), 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. Saadatseresht et al. propose path selection for evacuation planning with the help of the multi-objective evolutionary algorithm, where multiple factors, i.e. the distance from refuges, the capacity of refuges, and the population, are considered (Mohammad et al, 2009). 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

In this section, we introduce the overview of automatic evacuation guiding scheme in (Komatsu et al, 2018). Note that we slightly extend it by adding a function to

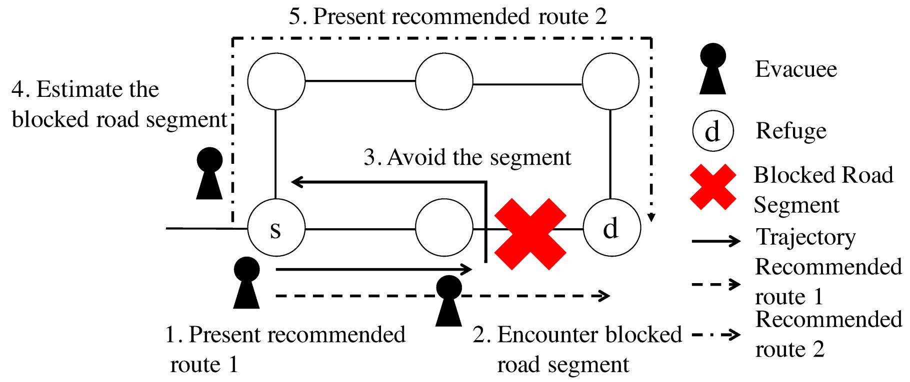

Fig. 1 Flow of evacuation guiding.

collect information about passable road segments, which will be used to calculate the reliability of evacuation path. (See details in Section 4.2.)

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} ($I_{\mathrm{M}} > 0$) 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 of refuges, in advance. When a disaster occurs, the application is initiated automatically. The application first finds out the nearest refuge $d \in \mathcal{V}$ from location $s \in \mathcal{V}$ of evacuee n. Next it calculates an evacuation route $r_{n,s,d}$ and presents him/her the route as the recommended route (Step 1 in Fig. 1). Recommended route $r_{n,s,d}$ 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 $r_{n,s,d}$. When evacuee n discovers a blocked road segment during his/her evacuation along recommended route $r_{n,s,d}$ (Step 2 in Fig. 1), he/she will take an 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 intervals of I_{M}. As a result, the application can detect 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 road segment e into a set of blocked road segments,

$\mathcal{E}_n^{\mathrm{NG}}$ (Step 4 in Fig. 1). If newly discovered blocked road segment e is included in the recommended route, the application further recalculates a new evacuation route $r_{n,s',d}$, which does not include blocked road segment e in $\mathcal{E}_n^{\mathrm{NG}}$, and presents him/her the route, from the current location s' to the nearest refuge d (Step 5 in Fig. 1). On other hand, when evacuee n has passed road segment $e \in \mathcal{E}$ during his/her evacuation, the application automatically records e into a set of passable road segments, $\mathcal{E}_n^{\mathrm{OK}}$.

When the mobile device can communicate with other mobile devices and/or the remaining communication infrastructures, it tries to obtain new information about blocked road segments and passable road segments. If these newly obtained blocked road segments are included in the recommended route, the application also recalculates a new evacuation route as in the above mentioned detection case. On the other hand, the newly obtained information about passable road segments will be used in the future route recalculation. Evacuation guiding for evacuee n finishes when he/she reaches the refuge or the application cannot find out any evacuation route to the refuge.

4 Proposed Scheme

In (Komatsu et al, 2018), the shortest path is applied as the recommended route for quick evacuation. In case of an earthquakes, 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 section, we propose a speedy and reliable path selection for the automatic evacuation guiding.

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 (City of Nagoya, 2015). Road blockage probability p_e $(0 \leq p_e \leq 1)$ is an estimated probability that road segment $e \in \mathcal{E}$ is blocked due to collapse of building along the road under a certain disaster. It is calculated based on the degree of collapse, the height of each building along the road and the width of the road. Let $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$ denote a risk map where $g : \mathcal{E} \to \mathbb{I}$ is a real-valued function that assigns blockage probability p_e in closed unit interval $\mathbb{I} = [0, 1]$ to each edge $e \in \mathcal{E}$.

4.2 Path Reliability

We define path reliability based on the road blockage probabilities. Since p_e is the road blockage probability, $1 - p_e$ indicates road passable probability that road segment e is passable. Path reliability can be defined as the probability that all roads $\forall e \in r$ on path r are passable. If road blockage probabilities are independent,

Algorithm 1 Mobile device n's enumeration of at most $k_{\max}$ shortest paths with constraint on path length, $\delta_{\max}$.

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Require: $\widehat{G} = (\mathcal{V}, \mathcal{E}, g), s, d, k_{\max}, \delta_{\max}$
Ensure: $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$
$\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}} = \emptyset$                              ▷ Initialize path candidates
$k = 1$
$r = k$-th_shortest_path$(\widehat{G}, n, s, d, k)$                     ▷ Obtain shortest path
$d_{\min} = f_{\mathrm{d}}(r)$
while $k \leq k_{\max}$ do                                   ▷ Enumerate at most $k_{\max}$ shortest paths
    if $f_{\mathrm{p}}(r) == 1$ then                          ▷ If successful route for evacuation is found
        return $\{r\}$
    $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}} = \mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}} \cup \{r\}$
    $k = k + 1$
    $r = k$-th_shortest_path$(\widehat{G}, n, s, d, k)$                 ▷ Obtain next candidate
    if $r =$ null or $f_{\mathrm{d}}(r) - d_{\min} > \delta_{\max}$ then      ▷ If proper next candidate is not found
        return $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$
return $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$
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path reliability is given by the product of road passable probabilities of all roads of the path,

$$f_{\mathrm{p}}(r) = \prod_{e \in r} (1 - p_e). \tag{1}$$

The path reliability takes a value in the range of $[0, 1]$ and a large (resp. small) value means high (resp. low) reliability.

We should note here that p_e of each road $e \in \mathcal{E}$ can be updated with the help of the automatic evacuation guiding (Komatsu et al, 2018). In the automatic evacuation guiding, each road segment is categorized into three states: unknown, passable, and blocked. All road segments initially starts from the unknown state. When a mobile device detects that road segment $e \in \mathcal{E}$ is passable (resp. blocked), p_e can be updated to zero (resp. one). These update will contribute to selecting more reliable path selection.

4.3 Short and Reliable Path Selection

We propose a speedy and reliable path selection based on a two-step approach, where we first enumerate candidates of short paths and then select the most reliable path from the candidates. The length of path r, i.e., path length, is given by the sum of the length of all roads composing path r:

$$f_{\mathrm{d}}(r) = \sum_{e \in r} d_e, \tag{2}$$

where d_e denotes the length of road $e \in \mathcal{E}$. We should note here that we can also apply traveling time of road e as the road cost, instead of road length. Since the traveling time of road e increases with the number of evacuees on that road, congestion-aware path selection can be achieved (Kasai et al, 2017).

Algorithm 1 presents the first step, i.e., mobile device n's enumeration of at most $k_{\max}$-shortest paths with constraint on path length, $\delta_{\max}$, which is the maximum increment from the shortest path. Given risk map $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$, current location $s \in \mathcal{V}$, destination $d \in \mathcal{V}$, $k_{\max}$, and $\delta_{\max}$, mobile device $n \in \mathcal{N}$ initializes the set of path candidates, $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$, to an empty set (line 1). Next, it calculates the shortest path r using k-th_shortest_path() function with $k = 1$ and uses its path length as the lower bound of path length, $d_{\min}$ (lines 2–4). Here, k-th_shortest_path() function can be achieved by existing algorithms, e.g., Yen's algorithm (Yen, 1971) and Pruned Landmark Labeling based approach (Akiba et al, 2015). Then, mobile device n sequentially enumerates at most $k_{\max}$-shortest paths with constraint on path length, $\delta_{\max}$ (lines 5–12). If it finds that r is a successful route for evacuation, which consists of only passable road segments, it stops the enumeration and returns the set of the most reliable route, i.e., $\{r\}$ (lines 6–7). Otherwise, it adds r to $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$ and tries to obtain the next candidate route as r (lines 8–10). If r is not found or the path length of r violates the constraint, it stops the enumeration and returns current candidates $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$ (lines 11–12). If there is no successful route for evacuation and no violation of path length constraint, it returns $k_{\max}$-shortest paths as $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$ (line 13). After obtaining path candidates $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$ using Algorithm 1, mobile device n selects a path with the largest path reliability as recommended route $r_{n,s,d}^{k_{\max},\delta_{\max}}$:

$$r_{n,s,d}^{k_{\max},\delta_{\max}} = \mathop{\arg\max}_{r \in \mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}} f_{\mathrm{p}}(r). \tag{3}$$

We can control the balance between speediness and safety of evacuation by appropriately selecting $k_{\max}$ and $\delta_{\max}$. In case of $k_{\max} = 1$, the proposed path selection is equivalent to the shortest path selection. If $k_{\max} = \delta_{\max} = \infty$, the proposed path selection adopts the most reliable path without taking into account of path length. Basically, small (resp. large) $k_{\max}$ and/or $\delta_{\max}$ emphasize speedy (resp. safe) evacuation but these two parameters have different roles. $k_{\max}$ guarantees the quantity of candidate paths while $\delta_{\max}$ guarantees the quality of them in terms of speediness of evacuation.

The appropriate values of these two parameters highly depend on the structure of road network. In Section 4.4, we will tackle this problem.

4.4 Determination of Appropriate Parameter Settings

It is desirable for evacuees to be able to determine appropriate values $k_{\max}^*$ and $\delta_{\max}^*$ for the two parameters $k_{\max}$ and $\delta_{\max}$ before disasters occur. In this section, we propose a parameter determination approach based only on risk map $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$, which can be retrieved in usual time. Suppose that evacuees start their evacuations from locations uniformly distributed in the area. Given $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$, $k_{\max}$, and $\delta_{\max}$, we can calculate an appropriate path $r_{s,d}^{k_{\max},\delta_{\max}}$ from each $s \in \mathcal{V}$ to destination $d \in \mathcal{V}$, according to Algorithm 1. Let $\delta_{s,d}^{k_{\max},\delta_{\max}}$ denote the increment of path length from the shortest path, i.e., $f_{\mathrm{d}}(r_{s,d}^{k_{\max},\delta_{\max}}) - f_{\mathrm{d}}(r_{s,d}^{1,0})$. The average $\overline{\delta}^{k_{\max},\delta_{\max}}$ of $\delta_{s,d}^{k_{\max},\delta_{\max}}$ among all $s \in \mathcal{V}$ can be regarded as the goodness

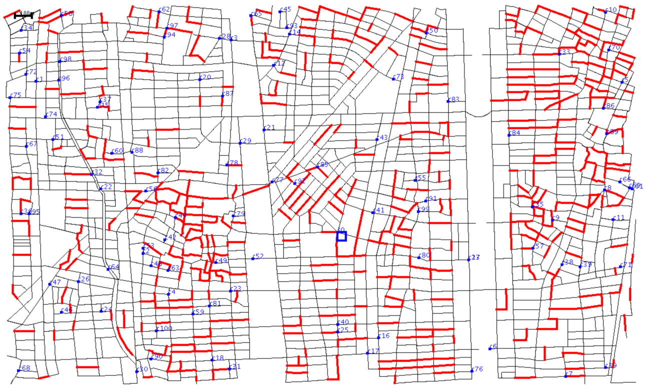

Fig. 2 Simulation area: $3,700$ [m] $\times$ $2,200$ [m] southwest area of Nagoya station in Japan.

of $(k_{\max}, \delta_{\max})$ in terms of path length. On the other hand, the average $\overline{f}_{\mathrm{p}}^{k_{\max},\delta_{\max}}$ of $f_{\mathrm{p}}(r_{s,d}^{k_{\max},\delta_{\max}})$ among all $s \in \mathcal{V}$ can be regarded as the goodness of $(k_{\max}, \delta_{\max})$ in terms of path reliability.

Suppose that search space $\mathbf{S}$ is given by direct product $\mathbf{K} \times \mathbf{\Delta}$, where $\mathbf{K}$ (resp. $\mathbf{\Delta}$) is the space of values that $k_{\max}$ (resp. $\delta_{\max}$) can take on. Since there is a trade-off between path length and path reliability, we introduce parameter δ_{th} to control this trade-off. We first find space $\mathbf{S}_{\delta_{\mathrm{th}}}$ in which $\overline{\delta}^{k_{\max},\delta_{\max}}$ is not more than predetermined threshold δ_{th} as follows:

$$\mathbf{S}_{\delta_{\mathrm{th}}} = \{(k_{\max}, \delta_{\max}) \in \mathbf{S} \mid \overline{\delta}^{k_{\max},\delta_{\max}} \leq \delta_{\mathrm{th}}\}.$$

We assume that each evacuee can set δ_{th} to tell the system his/her sensitivity to speediness of evacuation. Next, we obtain appropriate values $k_{\max}^*$ and $\delta_{\max}^*$, which maximize the path reliability:

$$(k_{\max}^*, \delta_{\max}^*) = \underset{(k_{\max},\delta_{\max}) \in \mathbf{S}_{\delta_{\mathrm{th}}}}{\arg\max} \ \overline{f}_{\mathrm{p}}^{k_{\max},\delta_{\max}}. \tag{4}$$

Numerical examples of parameter determination will be given in Section 5.2.

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 (Keränen et al, 2009). 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 blue square in Fig. 2) at a speed of 1.11 [m/s].

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 AP's are placed in $M \times M$ grid arrangement. We define *coverage* as the ratio of the area of roads included in the transmission ranges of APs to the whole area of all roads. We can control the coverage by changing M.

As for disaster scenarios, we initially set all road segments $e \in \mathcal{E}$ to be passable. Then, for each road segment e, we change the state of road segment e to be blocked with road blockage probability p_e. Fig. 2 shows an example of allocation of blocked road segments, where 17.2% road segments are blocked and highlighted by red color. 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. Recall that the evacuee's application can automatically detect and record a blocked road segment from the difference between recommended route and actual evacuation route at intervals of I_{M}, as mentioned in Section 3.2.

We use two kinds of evaluation criteria. The first one is the total number of encounters with blocked road segments of all evacuees, B, which is related to the safety of evacuation. The second one is the average (resp. maximum) evacuation time among evacuees, $\overline{T}$ (resp. $T_{\max}$), to evaluate the speediness of evacuation. Here, we define the evacuation time as the time interval from evacuation start to the evacuation completion. In what follows, simulation results are the average of 50 independent simulation experiments.

5.2 Validity of Parameter Determination Approach

In this section, we examine the validity of the parameter determination approach through numerical examples. We first show the numerical examples of parameter determination approach when setting search space $\mathbf{S} = \mathbf{K} \times \mathbf{\Delta}$ to be $\mathbf{K} = (1, 2, \ldots, 50)$ and $\mathbf{\Delta} = (0, 1, \ldots, 100)$. Fig. 3 illustrates $\mathbf{S}_{\delta_{\mathrm{th}}}$ and $(k^*_{\max}, \delta^*_{\max})$ for the risk map (Fig. 2) when δ_{th} is set to be 5, 10, and 15. Recall that there is a trade-off between path length and path reliability. Basically, path length (resp. path reliability) tends to become short (resp. high) in left bottom (resp. right top) area of $\mathbf{S}$. Three curves indicate the boarder lines of $\mathbf{S}_{\delta_{\mathrm{th}}}$ in case of $\delta_{\mathrm{th}} = 5$, 10, and 15, respectively. Each curve and its left area corresponds to $\mathbf{S}_{\delta_{\mathrm{th}}}$. We observe that $\mathbf{S}_{\delta_{\mathrm{th}}}$ expands to the upper right area with increase of δ_{th}. We also find out that each curve shows inversely proportional relationship between $k_{\max}$ and $\delta_{\max}$, so as to avoid increase of δ_{th}. The parameter settings on each curve has the same performance of path length but may have different path reliability. A star on each curve indicates $(k^*_{\max}, \delta^*_{\max})$ given by (4). Since large $k_{\max}$ can provide evacuees with many candidates of evacuation routes, $(k^*_{\max}, \delta^*_{\max})$ tends to have large $k_{\max}$.

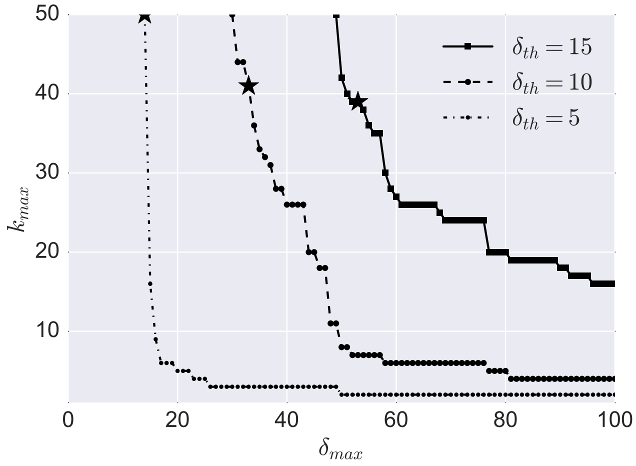

Fig. 3 $\mathbf{S}_{\delta_{\text{th}}}$ and $(k^*_{\text{max}}, \delta^*_{\text{max}})$ for risk map in Fig. 2 ($\delta_{\text{th}} = 5$, 10, and 15).

Table 1 Comparison between $\min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} \overline{T}(k_{\text{max}}, \delta_{\text{max}})$ and $\overline{T}(k^*_{\text{max}}, \delta^*_{\text{max}})$.

δ_{th}	$\overline{T}(k^*_{\text{max}}, \delta^*_{\text{max}})$	$\min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} \overline{T}(k_{\text{max}}, \delta_{\text{max}})$
5	1518	1518
10	1515	1514
15	1516	1513

In this scenario, $(k^*_{\text{max}}, \delta^*_{\text{max}})$ becomes $(50, 14)$, $(41, 33)$, and $(39, 53)$, for $\delta_{\text{th}} = 5$, 10, and 15, respectively.

Next, we examine the validity of obtained parameters $(k^*_{\text{max}}, \delta^*_{\text{max}})$ by analyzing the simulation results obtained over the same search space $\mathbf{S}$ and δ_{th}, which are used in the parameter determination approach. Note that coverage is set to be 100%. Through simulation experiments with parameter settings $(k_{\text{max}}, \delta_{\text{max}})$, we can obtain average evacuation time $\overline{T}(k_{\text{max}}, \delta_{\text{max}})$ and total number of encounters with blocked road segments, $B(k_{\text{max}}, \delta_{\text{max}})$. We can conclude that obtained parameters $(k^*_{\text{max}}, \delta^*_{\text{max}})$ are valid when the following two conditions are satisfied. First, $\overline{T}(k^*_{\text{max}}, \delta^*_{\text{max}}) - \min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} \overline{T}(k_{\text{max}}, \delta_{\text{max}})$ is not more than the allowable increase of evacuation time, i.e., $\delta_{\text{th}}/1.11$. Second, there is almost no difference between $B(k^*_{\text{max}}, \delta^*_{\text{max}})$ and $\min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} B(k_{\text{max}}, \delta_{\text{max}})$. Table 1 presents comparison between $\min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} \overline{T}(k_{\text{max}}, \delta_{\text{max}})$ and $\overline{T}(k^*_{\text{max}}, \delta^*_{\text{max}})$. We observe that $\overline{T}(k^*_{\text{max}}, \delta^*_{\text{max}}) - \min_{(k_{\text{max}},\delta_{\text{max}})\in\mathbf{S}} \overline{T}(k_{\text{max}}, \delta_{\text{max}})$ is 0 [s] ($\delta_{\text{th}} = 5$), 1 [s] ($\delta_{\text{th}} = 10$), and 3 [s] ($\delta_{\text{th}} = 15$), that is, the first condition is satisfied. Table 2 illustrates $B(k^*_{\text{max}}, \delta^*_{\text{max}})$ and statistics of $B(k_{\text{max}}, \delta_{\text{max}})$, i.e., minimum, mean, and standard deviation. We find that there is almost no difference between $B(k^*_{\text{max}}, \delta^*_{\text{max}})$ and the minimum of $B(k_{\text{max}}, \delta_{\text{max}})$, that is, the second condition also holds.

Table 2 $B(k^*_{\max}, \delta^*_{\max})$ and statistics of $B(k_{\max}, \delta_{\max})$, i.e., minimum, mean, and standard deviation.

δ_{th}	$B(k^*_{\max}, \delta^*_{\max})$	$B(k_{\max}, \delta_{\max})$ minimum	mean	standard deviation
5	95	95	106	6.2
10	89	89	100	8.2
15	87	86	96	8.1

5.3 Effectiveness of Proposed Scheme

In this section, we evaluate the effectiveness of the proposed scheme with appropriate parameter settings. In what follows, we use the case of $\delta_{\mathrm{th}} = 15$, where the appropriate parameter settings are $(k^*_{\max}, \delta_{\max}) = (39, 53)$. Since the performance of the proposed scheme depends on communication environments, we change the coverage of infrastructures in the range of [0,100]. We compare the performance of the proposed scheme with the following evacuation schemes.

- Ideal evacuation, in which all evacuees know the information about all blocked road segments before the evacuation starts. The ideal evacuation demonstrates the lower bound of the evacuation time of the proposed scheme.
- Automatic evacuation guiding based on shortest path selection (Komatsu et al, 2018), which is equal to the proposed scheme with $k_{\max} = 1$ and $\delta_{\max} = 0$.

5.3.1 Total Number of Encounters with Blocked Road Segments

We first evaluate the evacuation safety in terms of total number of encounters with blocked road segments. There are two functions that contribute to safety of evacuation by reducing the number of encounters with blocked road segments. First one is sharing of information about blocked road segments among mobile devices, which is a reactive function provided by the automatic evacuation guiding. Second one is reliable path selection based on geographical risk analysis, which is a proactive function provided by the proposed scheme. Note that the proposed scheme has both functions while the automatic evacuation guiding based on shortest path selection has only the first function of information sharing.

We first focus on the impact of geographical risk analysis by evaluating both schemes in an offline case where the information sharing is completely unavailable due to lack of both mobile-to-mobile direct communication and communication infrastructures. In the offline case, the proposed scheme can reduce the number of encounters with blocked road segments by 45.7% compared with the shortest path selection. This contribution is yielded by the geographic risk analysis.

Next, we focus on the impact of information sharing on the evacuation safety. Fig. 4 illustrates the transition of the number of encounters with blocked road segments when changing the coverage of communication infrastructures. We show the results of proposed scheme and the shortest path selection. Note that the 0% coverage case is different from the offline case because direct wireless communication between mobile devices is still available in the 0% coverage case. In the 0% coverage case, the proposed scheme can reduce the number of encounters with blocked road segments by 50.3% compared with that in the offline case. This improvement

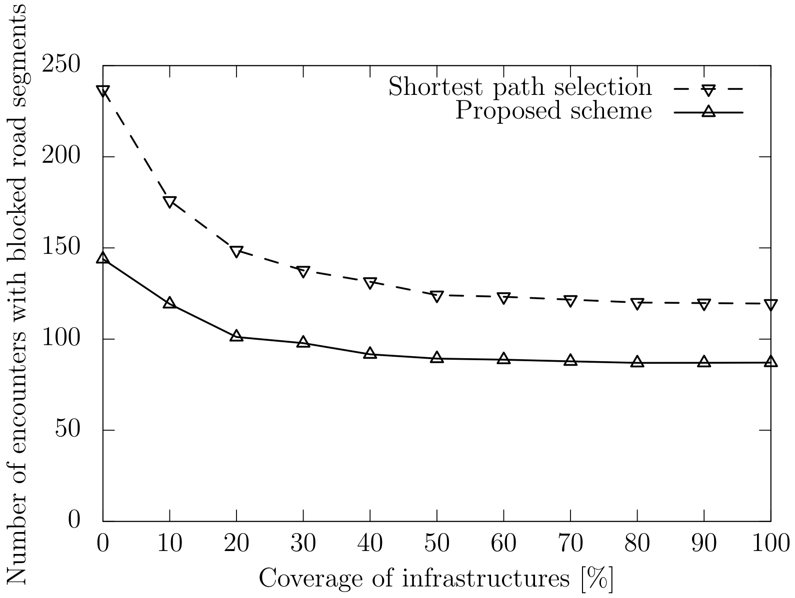

Fig. 4 The number of encounters with blocked road segments.

is achieved by the information sharing based on direct wireless communication between mobile devices.

Next, we focus on the information sharing through communication infrastructures. We observe that the number of encounters with blocked road segments monotonically decreases with coverage. In case of the proposed scheme, the performance improvement is almost saturated at the 20% coverage and becomes the maximum, i.e., 39.5% improvement, at the 100% coverage. From the viewpoint of comparison between two schemes, we confirm that the proposed scheme can reduce the number of encounters with blocked road segments from 27.1% (100% coverage) to 39.2% (0% coverage), compared with the shortest path selection. From the above results, we can conclude that the proposed scheme is robust against the damage of communication environments.

5.3.2 Evacuation Time

In Section 5.3.1, we showed that the proposed scheme with appropriate parameters can reduce the number of encounters with blocked road segments, regardless of coverage. However, reliable path selection with increase of $k_{\max}$ and $\delta_{\max}$ may also make evacuation routes longer. In this section, we evaluate the effectiveness of the proposed scheme in terms of average evacuation time and maximum evacuation time.

We first focus on the impact of geographical risk analysis by evaluating both schemes in the offline case. In the offline case, the average (resp. maximum) evacuation time of the proposed scheme becomes 1656 [s] (resp. 3573 [s]), which is 6.1% (resp. 10.2%) smaller than that of the shortest path selection, i.e. 1763 [s] (resp. 3979 [s]). These counter-intuitive results can be explained as follows. The

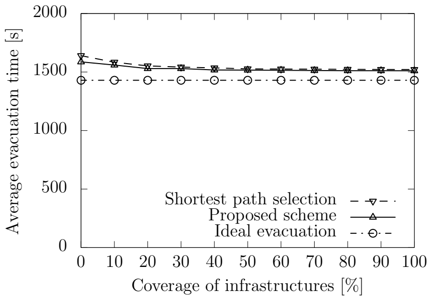

Fig. 5 Average evacuation time.

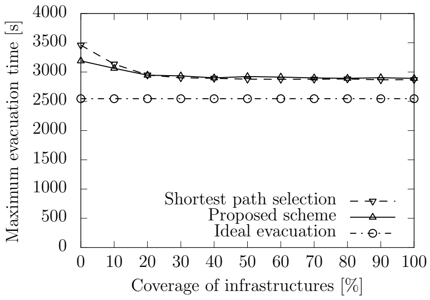

Fig. 6 Maximum evacuation time.

shortest path selection always presents shorter but less reliable evacuation routes than the proposed scheme. In the offline case, evacuees move to the refuges without help of other evacuees' information about blocked road segments. Under such situations, the shortest path selection tends to result in wasteful evacuation behavior caused by encountering with blocked road segments. On the contrary, the proposed scheme can alleviate such wasteful evacuation behavior with the help of reliable path selection based on geographical risk analysis.

Next, we focus on the impact of information sharing. Fig. 5 (resp. Fig. 6) illustrates the transition of average (resp. maximum) evacuation time when changing coverage of communication infrastructures. We show the results of three evacuation schemes: the proposed scheme, automatic evacuation guiding with shortest path selection, and ideal evacuation. We observe that the average (resp. maximum) evacuation time monotonically decreases with increase of coverage. In particular, the proposed scheme in the 0% coverage case can reduce the average (resp. maximum) evacuation time by 4.1% (resp. 10.7%) smaller than that in the offline case. This improvement comes from the information sharing through direct wireless communication between mobile devices. In addition, the proposed scheme can improve the average (resp. maximum) evacuation time by 3.2% (resp. 7.8%) compared with the shortest path selection, in case of the 0% coverage case.

We also find that both schemes can decrease both average and maximum evacuation times with increase of coverage. Direct wireless communication between mobile devices is effective for densely populated mobile devices. On the other hand, mobile devices isolated from others will require the help of communication infrastructures. Note that the performance improvement is almost saturated when the coverage is 30%, which is relatively small. From above results, we can conclude that the proposed scheme can improve both average and maximum evacuation times even under inferior communication environments.

6 Conclusion

When a large-scale disaster occurs, evacuees have to evacuate to the refuge quickly and safely. Most of the existing evacuation guiding schemes have been focusing on the speedy evacuation based on the shortest path selection. In this paper, we proposed a geographical risk analysis based path selection for speedy and reliable evacuation guiding. The proposed scheme first enumerates candidates of short paths from the evacuee's current location to the destination. Next, it selects the route with the highest path reliability based on geographical risk analysis from the candidates. Since the appropriate parameters of the proposed scheme depend on the structure of road network, we also proposed a parameter determination approach only based on the risk map, which can be retrieved in usual time.

Through simulation experiments, we first showed the validity of the determination approach. Next, we found that the proposed scheme could improve the safety of evacuation while keeping the average and maximum evacuation times unchanged compared with the shortest path selection, regardless of the communication environments. Specifically, the proposed scheme could reduce the number of encounters with blocked road segments by 45.7%, 39.2%, and 27.1%, compared with the shortest path selection, in case of the offline case, 0% coverage case, and 100% coverage case, respectively. We further demonstrated how the proactive function, i.e., geographical risk analysis, and the reactive function, i.e., information sharing, contribute to the system performance. As a result, we found that the geographical risk analysis and the information sharing through the direct wireless communication between mobile devices were much more important under severe communication environments. In addition, we also observed that the information sharing through the communication infrastructures still played an important role of supporting evacuees isolated from others.

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