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Speedy and Reliable Path Selection Based on Geographical Information Analysis for Automatic 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 thesis, 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. The proposed scheme first enumerates multiple shortest paths from the evacuee's current location to the refuge. Then, it selects the most reliable one from the candidates by taking account of road blockage probabilities, each of which is an estimated probability that the corresponding road is blocked under a certain disaster. Since the proposed scheme includes parameters to control the balance between speediness and safety, we also propose a parameter determination approach based on the risk map and geographical population distribution, which can be retrieved in usual time. Through simulation experiments, we first show the validity of the parameter determination approach. Next, we show that the proposed scheme can improve

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the safety of evacuation in terms of the number of encounters with blocked road segments, compared with the shortest path selection. In addition, the proposed scheme can also reduce both average and maximum evacuation times compared with the shortest path selection under severe communication environments. We show that the initial locations of evacuees affect the difficulty of finding speedy and reliable routes from viewpoint of the proactive approach. In terms of the reactive approach, the initial locations and the number of evacuees do not only affect the opportunities of information sharing but also the degree of evacuation improvement. Finally, we also find that the evacuation performance can be maintained even if the evacuees cannot accurately grasp the disaster magnitude and are forced to use the risk map with the maximum class.

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 [1]. 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 [2], where communication among mobile devices is enabled by Delay Tolerant Networks (DTNs) [3]. 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 preinstalled into his/her mobile device in usual time. The application calculates an evacuation route from the current position to a refuge, based on the map and the 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 [2], the effectiveness of the automatic evacuation guiding 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 [4]. (See the details in Section 4.1.2). We can also obtain information about geographical distribution of people in the usual time, e.g., location data collected from mobile phones and people flow data [5].

In this thesis, we propose a speedy and reliable path selection for the automatic evacuation guiding by using the geographical information about map, road blockage probabilities, and geographically population distribution in the usual time. 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 evacuation guiding with the reactive approach and proactive approach can improve evacuation movement in enormous damage environments, e.g., inferior communication environments.

The rest of this thesis is organized as follows. Chapter 2 gives related work. In Chapter 3, we explain the existing automatic evacuation guiding scheme. In

Chapter 4, the proposed scheme is presented, and Chapter 5 gives simulation results. Finally, Chapter 6 provides conclusions and future work.

2 Related Work

There are several existing studies on evacuation guiding supported by information and communication technology (ICT) [2, 6, 7]. 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 [6]. Fujihara and Miwa propose an evacuation guiding scheme using DTN under the situations of damage to communication infrastructures [7]. 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 [2]. 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 thesis, 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.

There are several existing studies on the risk analysis after a disaster occurs [4, 8, 9]. 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 [4]. Church and Cova map evacuation risks on transportation networks using a spatial optimization model, called critical cluster model, in which the whole area is dividied into multiple small areas, and the small areas with high ratio of population to exit capacity are regarded as those with high evacuation risk [8]. Since the model in [8] 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 [9]. In this thesis, we improve the safety of evacuation guiding by taking into account of 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. [10, 11, 12]. There are two kinds of definitions of road network reliability: connectivity reliability and travel time reliability [10]. 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 [10]. Chen et al. analyze a road network with traffic demands by considering the connectivity reliability, the travel time reliability, and the capacity reliability [11]. Ahuja et al. propose a method to calculate the path reliability from the reliability of each link of the path [12].

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 [13, 14, 15]. In [13], Yuan and Wang propose path selection models for emergency logistics management, with the help of an ant colony optimization algorithm [16], in order to select a route that minimizes both total travel time and route complexity. In [14], 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 [15]. In this thesis, 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 chapter, we introduce the overview of automatic evacuation guiding scheme in [2]. Note that we slightly extend it by adding a function to 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. 3.1 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. 3.1). Recommended route $r_{n,s,d}$ between

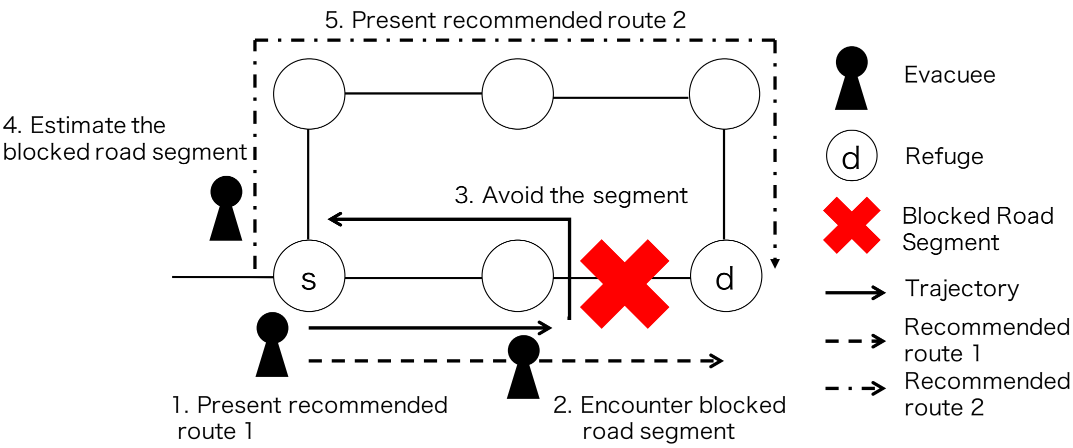

Figure 3.1: Flow of evacuation guiding.

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. 3.1), he/she will take an another route by his/her own judgement (Step 3 in Fig. 3.1). 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. 3.1). The application further recalculates a new evacuation route $r_{n,s',d}$, which does not include blocked road segments 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. 3.1). On the 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. These information will be used to recalculate the recommended route. 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 [2], the shrotest 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 chapter, we propose a geographical information analysis based path selection for the automatic, speedy, and reliable evacuation guiding.

4.1 Geographical Information

Nowadays, we can easily use digital maps, e.g., OpenStreetMap [17] and Google Maps [18], and some of them, e.g., OpenStreetMap, can also be used even under offline environments. Moreover, we can also obtain other types of geographical information, e.g., the geographical population distribution in usual time and geographical risk, in particular areas. Evacuees can prepare these geographical information using the mobile application in advance.

4.1.1 Geographical Population Distribution in Usual Time

The geographical population distribution in usual time is important because it affects the initial positions of evacuations. It can be generated by location data collected from mobile phones and/or people flow data [5]. In this thesis, we use the people flow data, which can be easily obtained. The people flow data is spatio-temporal information about movements of people, which is generated based on the person trip survey [19]. The person trip survey has been conducted for particular areas by Ministry of Land, Infrastructure and Transport and municipalities in Japan. It is a questionnaire survey that records the series of personal movements from origins to destinations, called trips. Since the person trip survey is applied to a limited number of people in the target area, an expansion factor is introduced to estimate the movement of the whole people in that area. The expansion factor of a trip means the number of people that follow that trip. Each trip is divided into one or more sub-trips such that each sub-trip has the same transportation method, e.g., walk, car, or train. Each sub-trip has some information, e.g., the origin, destination, travel time between them, and travel time. The people flow data are calculated by transforming each of sub-trip data into a series of the corresponding person's locations at a given interval, i.e., a minute. We can obtain the geographical people distribution at a certain period, e.g., one hour, by analyzing the people flow data.

4.1.2 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 [4]. 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, path reliability is given by the product of road passable probabilities of all roads of the path,

$$f_{\mathrm{p}}(r) = \prod_{e \in r}(1 - p_e). \tag{4.1}$$

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

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 $\mathcal{R}_{n,s,d}^{k_{\max},\delta_{\max}}$

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 [2]. In the automatic evacuation guiding, each road segment is categorized into three states: unknown, passable, and blocked. All road segments initially start 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 updates 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:

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

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 [20].

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, δ_{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 δ_{max}, mobile device $n \in \mathcal{N}$ initializes the set of path candidates, $\mathcal{R}_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$, 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 [21] and Pruned Landmark Labeling based approach [22]. Then, mobile device n sequentially enumerates at most k_{max}-shortest paths with constraint on path length, δ_{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 $\mathcal{R}_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$ 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 $\mathcal{R}_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$ (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 $\mathcal{R}_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$ (line 13). After obtaining path candidates $\mathcal{R}_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$ using Algorithm 1, mobile device n selects a path with the largest path reliability as recommended route $r_{n,s,d}^{k_{\mathrm{max}},\delta_{\mathrm{max}}}$:

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

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 Setting

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 the geographical information that can be retrieved in usual time, i.e., geographical population distribution in usual time and risk map $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$. Suppose that evacuees start their evacuations from initial locations, $\mathcal{V}_{\text{init}}$, which is obtained by the geographical people distribution. If the target area does not have information about the geographical people distribution, we assume that evacuee's initial locations are uniformly distributed in the area. Given $\widehat{G} = (\mathcal{V}, \mathcal{E}, g)$, $k_{\max}$, and $\delta_{\max}$, we can calculate an appropriate path $r^{k_{\max},\delta_{\max}}_{s,d}$ from each $s \in \mathcal{V}_{\text{init}}$ to the nearest destination $d \in \mathcal{V}$, according to Algorithm 1. Let $\delta^{k_{\max},\delta_{\max}}_{s,d}$ denote the increment of path length from the shortest path, i.e., $f_{\text{d}}(r^{k_{\max},\delta_{\max}}_{s,d}) - f_{\text{d}}(r^{1,0}_{s,d})$. The average $\overline{\delta}^{k_{\max},\delta_{\max}}$ of $\delta^{k_{\max},\delta_{\max}}_{s,d}$ among all $s \in \mathcal{V}_{\text{init}}$ nearest to $d \in \mathcal{V}$ can be regarded as the goodness of $(k_{\max}, \delta_{\max})$ in terms of path length. On the other hand, the average $\overline{f}^{k_{\max},\delta_{\max}}_{\text{p}}$ of $f_{\text{p}}(r^{k_{\max},\delta_{\max}}_{s,d})$ among all $s \in \mathcal{V}_{\text{init}}$ nearest to $d \in \mathcal{V}$ 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} for each $d \in \mathcal{V}$ 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:

$$(k^*_{\max}, \delta^*_{\max}) = \underset{(k_{\max},\delta_{\max}) \in \mathbf{S}_{\delta_{\mathrm{th}}}}{\arg\max} \; \overline{f}_{\mathrm{p}}^{k_{\max},\delta_{\max}}. \tag{4.2}$$

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 use The ONE Simulator [23]. We also use the risk map of $2,600$ [m]$\times 1,700$ [m] Arako area of Nagoya city in Japan, which is provided by Nagoya city (Fig. 5.1). This map's internal graph structure is composed of 939 vertices and $1,878$ directed edges. There are five refuges (d_1: Uchide nursery school, d_2: Maruike park, d_3: Arako primary school, d_4: Arako park, and d_5: Arako community center), which are presented by blue squares in Fig. 5.1. We set the simulation time to be $5,000$ [s]. When the simulation starts, a disaster occurs and the evacuees start moving from given points on the map (blue points in Fig. 5.1) to the nearest refuges at a speed of 1.11 [m/s]. Since all evacuees may require some time to start evacuation, the start time of each evacuation is randomly delayed from 0 to 200 seconds.

Because the initial positions of evacuees may affect the evacuation performance, we prepare different kinds of scenarios: random, commuting, and returning scenarios. In the random scenario, evacuees start evacuations from random positions. This scenario is regarded as the default scenario where the geographical population distribution in usual time cannot be obtained. To evaluate the impact on taking account of the geographical population distribution in usual time, we use the commuting and returning scenarios. In the commuting (resp. returning) scenario, the initial locations of evacuees are determined by the geographical population distribution at 8:00 (resp. 17:00), which is obtained by the people flow data of Nagoya city. People tend to move to a relatively small number of points,

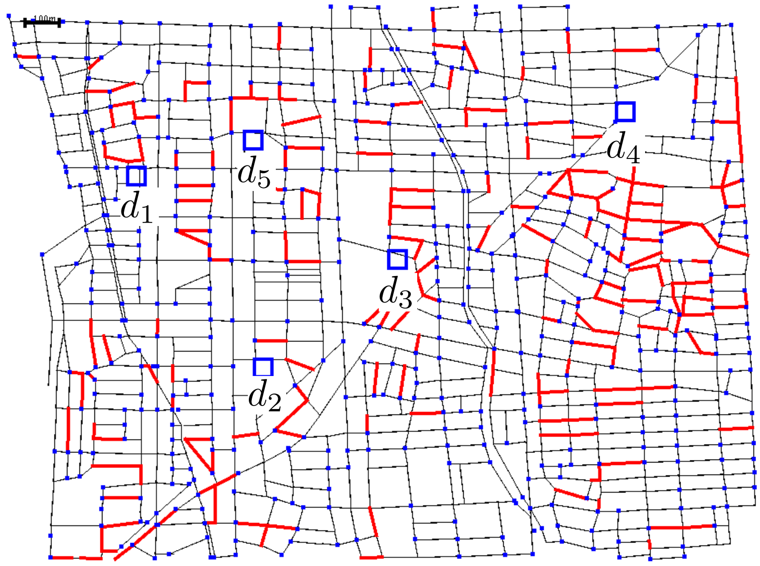

Figure 5.1: Risk map: $2,600$ [m] $\times\, 1,700$ [m] Arako area of Nagoya city in Japan.

e.g., companies and schools, in the commuting scenario while they tend to move to various points, e.g., home and stations, in the returning scenario. The number of evacuees are set to be 2,415 (resp. 705) in the commuting (resp. returning) scenario, which is equal to the number of pedestrians in the corresponding people flow data. For comparison purpose, we prepare two kinds of random scenarios: random scenario with $N = 705$ and that with $N = 2,415$.

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 $N \times N$ 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 N.

As for the disaster situations, we set the blocked road segments (red lines in Fig. 5.1) according to the road blockage probability of each edge on the graph.

Table 5.1: $\overline{T}(k^*_{\max}, \delta^*_{\max})$ and statistics of $\overline{T}(k_{\max}, \delta_{\max})$, i.e., minimum, mean, value of top 10%, and standard deviation.

δ_{th}	$\overline{T}(k^*_{\max}, \delta^*_{\max})$	$\overline{T}(k_{\max}, \delta_{\max})$			
		minimum	mean	top 10%	standard deviation
5	1266	1234	1299	1265	17.6
10	1262	1227	1280	1254	21.1
15	1252	1193	1272	1246	22.8

Nagoya city in Japan provides information of the road blockage probabilities for several classes depending on the degree of damages. In what follows, we use the data of maximum class that considers the possibility of all kinds of disasters.

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. 5.2 illustrates $\mathbf{S}_{\delta_{\text{th}}}$ and $(k^*_{\max}, \delta^*_{\max})$ for destination d_4 when δ_{th} is set to be 5, 10, and 15 in the random scenario ($N = 705$). 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 $\mathbf{S}_{\delta_{\text{th}}}$ in case of $\delta_{\text{th}} = 5$, 10, and 15, respectively. Each curve and its left area corresponds to $\mathbf{S}_{\delta_{\text{th}}}$. We observe that $\mathbf{S}_{\delta_{\text{th}}}$ expands to the upper

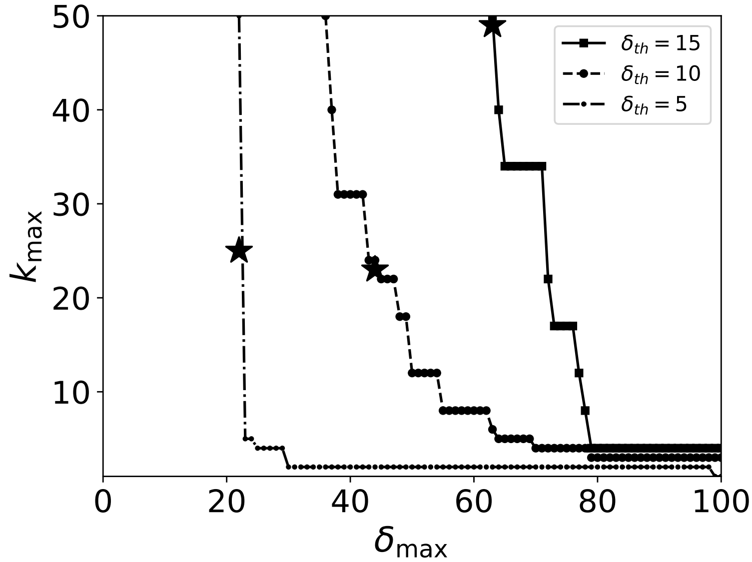

Figure 5.2: $\mathbf{S}_{\delta_{\text{th}}}$ and $(k^*_{\text{max}}, \delta^*_{\text{max}})$ for risk map in Fig. 5.1 (δ_{th} = 5, 10, and 15).

Table 5.2: $B(k^*_{\text{max}}, \delta^*_{\text{max}})$ and statistics of $B(k_{\text{max}}, \delta_{\text{max}})$, i.e., minimum, mean, value of top 10%, and standard deviation.

δ_{th}	$B(k^*_{\text{max}}, \delta^*_{\text{max}})$	$B(k_{\text{max}}, \delta_{\text{max}})$			
		minimum	mean	top 10%	standard deviation
5	1131	1075	1194	1135	46.7
10	1081	1022	1156	1085	58.8
15	1004	897	1120	1032	73.2

right area with increase of δ_{th}. We also find out that each curve shows inversely proportional relationship between k_{max} and δ_{max}, so as to avoid increase of δ_{th}. The parameter settings on each curve have the same performance of path length but may have different path reliability. A star on each curve indicates $(k^*_{\text{max}}, \delta^*_{\text{max}})$ given by (4.2). Since large k_{max} can provide evacuees with many candidates of evacuation routes, $(k^*_{\text{max}}, \delta^*_{\text{max}})$ tends to have large k_{max}. In this case, $(k^*_{\text{max}}, \delta^*_{\text{max}})$ becomes $(25, 22)$, $(23, 44)$, and $(49, 63)$, for δ_{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 the communication environment is offline. Through simulation experiments with parameter settings $(k_{\max}, \delta_{\max})$, we can obtain average evacuation time $\overline{T}(k_{\max}, \delta_{\max})$ and total number of encounters with blocked road segments, $B(k_{\max}, \delta_{\max})$. Table 5.1 (resp. Table 5.2) presents $\overline{T}(k^*_{\max}, \delta^*_{\max})$ (resp. $B(k^*_{\max}, \delta^*_{\max})$) and statistics of $\overline{T}(k_{\max}, \delta_{\max})$ (resp. $B(k_{\max}, \delta_{\max})$), i.e., minimum, mean, top 10%, and standard deviation. We observe that both $\overline{T}(k^*_{\max}, \delta^*_{\max})$ and $B(k^*_{\max}, \delta^*_{\max})$ cannot achieve the minimum for each δ_{th}. This is because the parameter determination approach only analyzes the risk map and cannot fully deal with the actual avoidance behavior that occurs at the encounters with blocked road segments. This limitation also causes the counterintuitive phenomenon where $\overline{T}(k^*_{\max}, \delta^*_{\max})$ decreases with increase of δ_{th}. In the parameter determination approach, we assume that the shortest path is passable but this assumption may not be true in the actual situation. Selecting more reliable path with increase of δ_{th} will also contribute to reducing the wasteful evacuation behavior caused by encountering blocked road segments. In spite of these difficulty in analyzing, the parameter determination approach can achieve the performance that is better than the mean and is competitive with the top 10% results.

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 $\delta_{\text{th}} = 15$ in the random scenario ($N = 705$). 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: All evacuees know the information about all blocked road segments at the start of their evacuations. The ideal evacuation demonstrates the lower bound of the evacuation time of the proposed scheme.
- Shortest path selection: All evacuees follow the automatic evacuation guiding based on shortest path selection [2]. Note that this is equivalent to the proposed scheme with $k_{\max} = 1$ and $\delta_{\max} = 0$.

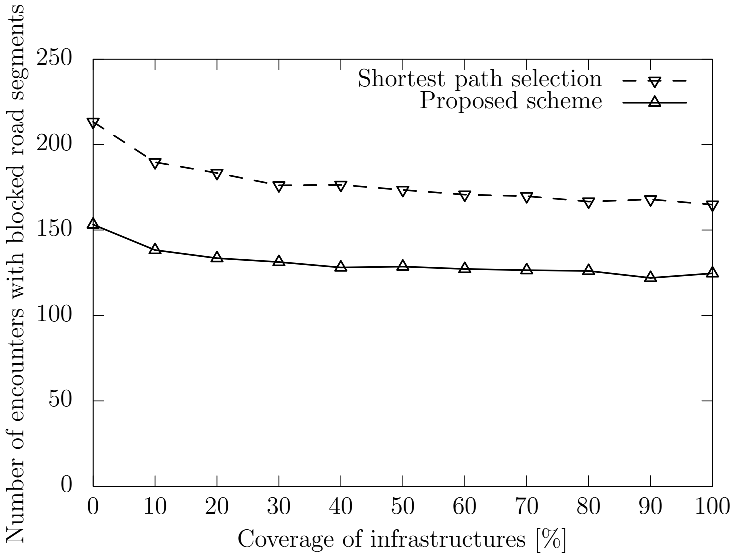

Figure 5.3: The number of encounters with blocked road segments.

5.3.1 Total Number of Encounters with Blocked Road Segments

Fig. 5.3 illustrates the transition of the number of encounters with blocked road segments when changing coverage of communication infrastructures. We show the results of proposed scheme and shortest path selection. 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 can confirm the effect of reliable path selection by comparing the results of two schemes. The proposed scheme can reduce the number of encounters with blocked road segments compared with the shortest path selection, e.g., 28.2% (0% coverage) and 24.2% (100% coverage). We also evaluate both schemes in an offline case where the information sharing is unavailable due to lack of both

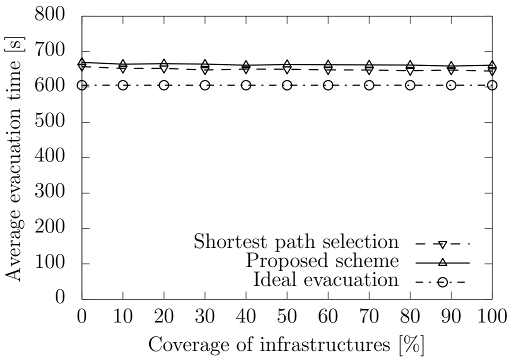

Figure 5.4: Average evacuation time.

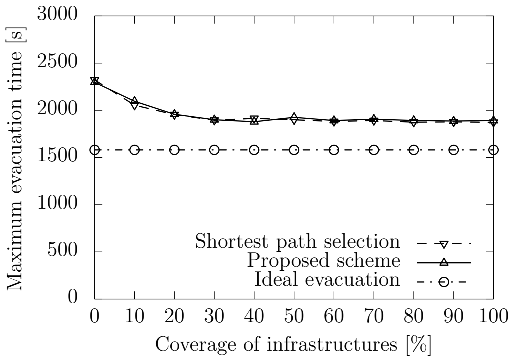

Figure 5.5: Maximum evacuation time.

mobile-to-mobile direct communication and communication infrastructures. In the offline case, the number of encounters with blocked road segments of the proposed scheme becomes 1235, which is much smaller than that of the shortest path selection, i.e., 1911.

Next, we focus on the impact of coverage on the evacuation safety. We observe that the number of encounters with blocked road segments monotonically decreases with coverage, regardless of schemes. In case of the proposed scheme, the performance improvement is almost saturated when the coverage is only 30%. 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 communication coverage. However, reliable path selection may also make evacuation routes longer with increase of $k_{\max}$ and $\delta_{\max}$. In this section, we evaluate the effectiveness of the proposed scheme in terms of average evacuation time and maximum evacuation time.

Fig. 5.4 (resp. Fig. 5.5) illustrates the transition of average (resp. maximum) evacuation time when changing coverage of communication infrastructures. We show the results of three evacuation schemes: proposed scheme, shortest path selection, and ideal evacuation. We first observe that the results of proposed scheme are competitive with those of shortest path selection, despite of selecting more reliable path, which may make the evacuation path longer. We also find that the coverage does not affect the average evacuation time but can improve the maximum evacuation time. This indicates that the information sharing through communication infrastructure is still important to reduce the evacuation time, especially for evacuees that tend to be isolated from others.

In the offline case, all evacuees are isolated with each other. We find that the average evacuation time of the proposed scheme becomes 779, which is shorter than that of shortest path selection, i.e. 801. This is because the shortest path selection may cause wasteful evacuation behavior by encountering blocked road segments, which can be alleviated by the reliable path selection. These results show that the proactive approach is more effective for the evacuation under inferior communication environments.

5.4 Impact of Initial Locations of Evacuees

In general, the geographical population distribution temporally varies according to the human life cycle. To reveal how the initial locations of evacuees and the number of evacuees affect the evacuation performance, we compare the results among four scenarios: random scenario with $N = 705$ (Fig. 5.6), random scenario with $N = 2,415$ (Fig. 5.7), commuting scenario with $N = 2,415$ (Fig.5.8), and returning scenario with $N = 705$ (Fig. 5.9). In what follows, we use the case of $\delta_{\text{th}} = 15$.

The locations of evacuees have complex effects on the evacuation. From the viewpoint of the proactive approach, the difficulty of finding speedy and reliable paths may change according to locations. In terms of the reactive approach, the locations of evacuees and the number of evacuees affect not only the opportunities of information sharing through device-to-device communication but also the degree of evacuation improvement yielded by the obtained information.

First, we focus on the impact of initial evacuees' locations on the proactive approach, which can be analyzed through the evaluation under the offline case. Table 5.3 illustrates the results, i.e., B, $\overline{T}$, and $T_{\max}$, in the four scenarios when the communication environment is offline. Because the number of evacuees in the

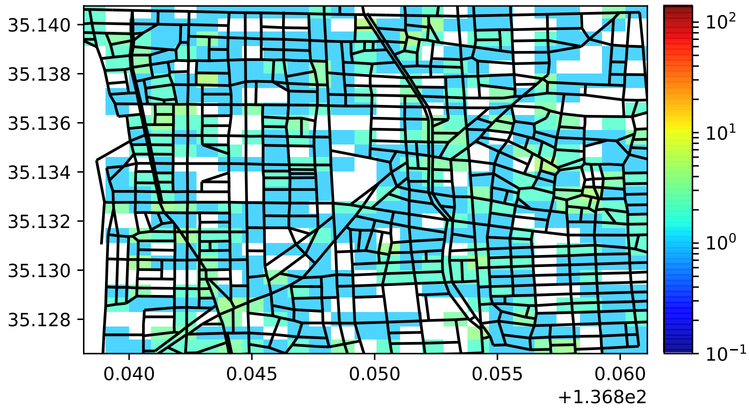

Figure 5.6: The initial locations of evacuees in the random scenario ($N = 705$).

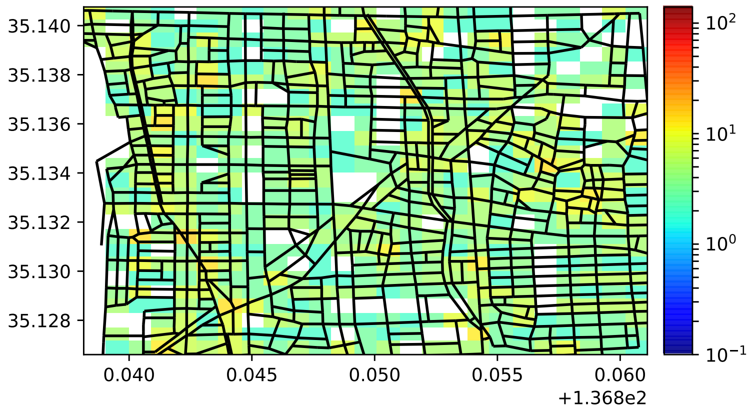

Figure 5.7: The initial locations of evacuees in the random scenario ($N = 2,415$).

commuting scenario, i.e., 2,415, is larger than that in the random and returning scenario, i.e., 705, we also give normalized B, which is the number of encounters with blocked road segments per evacuee. The results in the random scenario can be regarded as the average evacuation behavior that an evacuee starting from an arbitrary point will experience. We first observe that there is almost no difference between B in the commuting scenario and that in the random scenario ($N = 2,415$). We also find that $\overline{T}$ and $T_{\max}$ in the commuting scenario are less than those in the random scenario ($N = 2,415$), which indicates that evacuees in the commuting scenario are initially located at better places in terms of speediness. On the other hands, B in the returning scenario is greater than

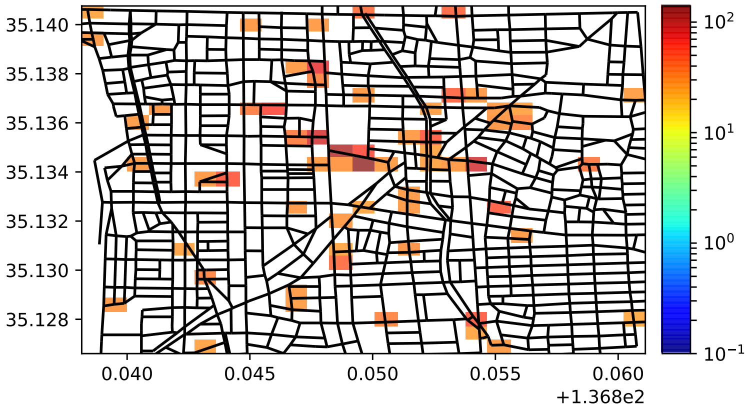

Figure 5.8: The initial locations of evacuees in the commuting scenario.

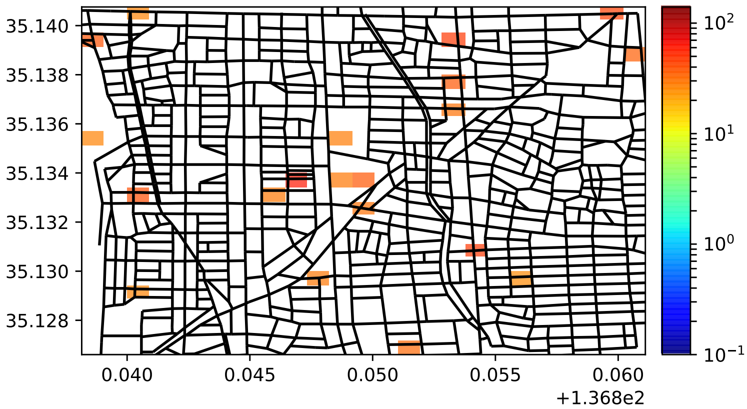

Figure 5.9: The initial locations of evacuees in the returning scenario.

that in the random scenario ($N = 705$), which indicates that evacuees in the returning scenario are initially located at worse places in terms of safety.

Second, we focus on the impact of initial evacuees' locations on the reactive approach. We first investigate the relationship between the initial locations and improvement degree of evacuation behavior yielded by information sharing. This can be analyzed through the evaluation under the 100% coverage case where evacuees can retrieve all the dynamic information, i.e., blocked road segments and passable road segments, in a real-time manner. Table 5.4 illustrates the results, i.e., B, $\overline{T}$, and $T_{\max}$, in the four scenarios when the communication environment is 100% coverage. Comparing Table 5.4 with Table 5.3, we find that

Table 5.3: $B, \overline{T}$, and $T_{\max}$ with the proposed scheme in four scenarios (offline case).

Scenario	B	$\overline{T}$	$T_{\max}$
Random scenario ($N = 2,415$)	2919 (1.21)	726	3736
Commuting scenario ($N = 2,415$)	3078 (1.27)	628	2587
Random scenario ($N = 705$)	1235 (1.75)	779	3058
Returning scenario ($N = 705$)	1451 (2.06)	865	2965

Table 5.4: $B, \overline{T}$, and $T_{\max}$ with the proposed scheme in four scenarios (100% coverage case).

Scenario	B	$\overline{T}$	$T_{\max}$
Random scenario ($N = 2,415$)	260 (0.11)	632	1938
Commuting scenario ($N = 2,415$)	614 (0.25)	568	1957
Random scenario ($N = 705$)	125 (0.18)	662	1891
Returning scenario ($N = 705$)	338 (0.49)	782	2391

the improvement ratio of B in the 100% coverage case to that in the offline case becomes 91.1%, 80.1%, 89.9%, and 76.7%, in the random ($N = 2,415$), commuting, random ($N = 705$), and returning scenarios, respectively. Since the initial locations are well distributed over the area in the random scenarios (Figs. 5.6 and 5.7), each evacuee can easily obtain useful information from preceding evacuees. In the commuting and returning scenarios, evacuees initially tend to form groups as in Figs. 5.8 and 5.9. The improvement ratio in the commuting scenario becomes larger than that in the returning scenario because of the larger number of evacuees and the denser distribution of groups.

Next, we focus on the results in the 0% coverage case, which can reveal how the device-to-device communication improves the evacuation performance. Table 5.5 illustrates the results, i.e., B, $\overline{T}$, and $T_{\max}$, in the four scenarios when the communication environment is 0% coverage and only the device-to-device is available. Comparing the results of random scenario ($N = 705$) and those of random scenario ($N = 2,415$), we can confirm that larger N yield better results, which come from the more opportunities for device-to-device communication. We

Table 5.5: $B, \overline{T}$, and $T_{\max}$ with the proposed scheme in four scenarios (0% coverage case).

Scenario	B	$\overline{T}$	$T_{\max}$
Random scenario ($N = 2,415$)	277 (0.11)	634	1939
Commuting scenario ($N = 2,415$)	711 (0.29)	574	2245
Random scenario ($N = 705$)	153 (0.22)	670	2297
Returning scenario ($N = 705$)	419 (0.59)	798	2667

Table 5.6: The result of the proposed scheme used in the risk map of each class.

Risk-map class	Offline			100% coverage		
	B	$\overline{T}$	$T_{\max}$	B	$\overline{T}$	$T_{\max}$
Maximum class	542	508	1330	110	496	1279
Historical class	550	509	1323	113	496	1270

also find that the results of commuting scenario are better than those of returning scenario. This is because of not only the larger number of evacuees but also the denser distribution of evacuees. In other words, the coverage of communication infrastructure is more important when the evacuees are sparsely distributed over the area.

5.5 Impact of Risk-Map Accuracy

Recall that the road blockage probabilities in risk map depend on the magnitude of disaster. For example, Nagoya city provides the road blockage probabilities of two classes: maximum class and historical class. The maximum class considers all kinds of disaster risks while the historical class is based on the maximum disaster in recorded history. However, it may be difficult to prepare the road blockage probabilities corresponding to the actual magnitude of disaster and/or judge the actual disaster magnitude precisely at the start of evacuation. One possible way to cope with this problem is using the risk map with maximum class.

Suppose that the disaster causes the blocked road segments according to the road blockage probability of the historical class. In what follows, we show how

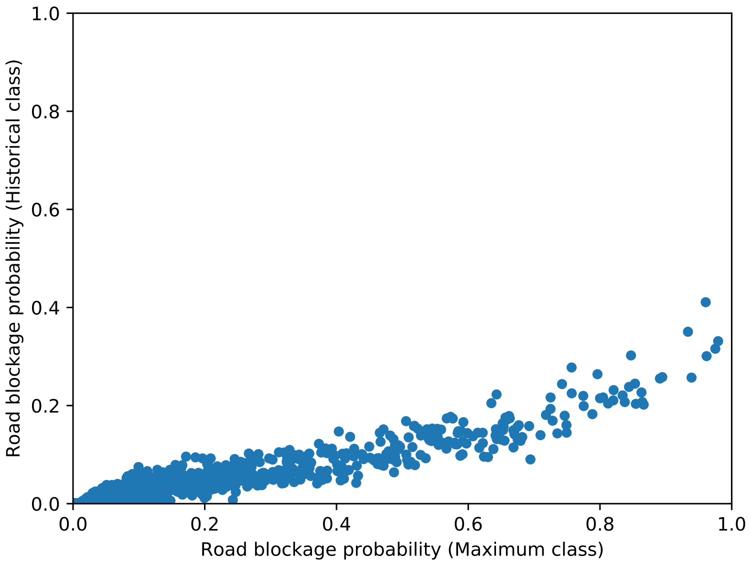

Figure 5.10: Correlation between road blockage probabilities of maximum class and those of historical class.

the performance of proposed scheme changes depending on the class of risk map. We use $\delta_{\mathrm{th}} = 15$ and the commuting scenario. Table 5.6 presents the result of the proposed scheme with the two classes of risk maps. Since the results of risk map with maximum class are similar to those of risk map with historical class, the mismatch of risk-map class does not much affect the system performance.

To reveal this reason, we show the correlation between road blockage probabilities of maximum class and those of historical class in Fig. 5.10. We observe that there is a strong correlation between them and the correlation coefficient becomes 0.949. In the proposed scheme, the application first calculates the top k-shortest route candidates and then selects the most reliable route based on path reliability (4.1). The top k-shortest route candidates is exactly the same, regardless of the risk-map class, but the path reliability will change depending on the risk-map class. The risk map with maximum class tends to suggest more reliable path than that with historical class but these two paths also tend to be similar due to the high correlation coefficient of blockage probabilities.

6 Conclusion

When a large-scale disaster occurs, evacuees have to evacuate to refuges speedily and safely. Most of the existing evacuation guiding schemes have been focusing on the speedy evacuation based on the shortest path selection. In this thesis, we proposed a geographical risk analysis based path selection for speedy and reliable evacuation guiding. The proposed scheme first enumerated multiple shortest paths from the evacuee's current location to the destination. Next, it selected 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 based on the risk map and geographical population distribution, which can be retrieved in usual time.

Through simulation experiments, we first showed the validity of parameter determination approach. Next, we found that the proposed scheme can improve the safety of evacuation in terms of the number of encounters with blocked road segments, compared with the shortest path selection, regardless of the communication environments. In addition, the proposed scheme can also improve both average and maximum evacuation times, compared with the shortest path selection under the severe communication environments. We further showed that the initial locations of evacuees affect the difficulty of finding speedy and reliable routes in terms of the proactive approach. From the viewpoint of the reactive approach, the initial locations and the number of evacuees also affect the opportunities of information sharing as well as the degree of evacuation improvement. Finally, we also found that the evacuation performance can be kept even if the evacuees cannot precisely grasp the disaster magnitude and are forced to use the risk map with the maximum class.

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Publication List

International Conference

1. Takanori Hara, Masahiro Sasabe, Shoji Kasahara, “Short and Reliable Path Selection for Automatic Evacuation Guiding Based on Interactions between Evacuees and Their Mobile Devices,” M. Younas, A. Irfan and H. Irena Eds., Mobile Web and Intelligent Information Systems (in Proc. of The 14th International Conference on Mobile Web and Intelligent Information Systems (MobiWIS 2017), Prague, Czech Republic, Aug. 2017.), LNCS, vol. 10486, pp. 33-44, 2017. (Acceptance rate: 35%.)

Domestic Conference

1. 原 崇徳, 笹部 昌弘, 笠原 正治, “避難者 · 端末間連携型自動避難誘導方式における距離と道路リスクに基づく経路選択方式,” インターネット技術 163 委員会新世代ネットワーク構築のための基盤技術研究分科会ワークショップ, Sept. 2017. (ポスター発表)
2. 原 崇徳, 笹部 昌弘, 笠原 正治, “避難者 · モバイル端末間連携型自動避難誘導における経路長と経路信頼性を考慮した避難経路選択方式に関する一検討,” 第 41 回インターネット技術第 163 委員会研究会, May 2017.
3. 原 崇徳, 笹部 昌弘, 笠原 正治, “避難者 · モバイル端末間連携型自動避難誘導における経路の長さと信頼性を考慮した避難経路選択方式に関する一検討,” 信学技報 (NS2016–247), vol.116, pp.517–522, Mar. 2017.
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5. 原 崇徳, 笹部 昌弘, 笠原 正治, “道路網におけるユーザの利己的行動と通信環境が分散型経路選択方式に与える影響 (Poster Presentation),” 第 5 回コミュニケーションクオリティ基礎講座ワークショップ, Jan. 2018. (ポスター発表)

Award

1. 第 5 回コミュニケーションクオリティ基礎講座ワークショップ 最優秀研究賞