RESEARCH ARTICLE

Congestion-aware route selection in automatic evacuation guiding based on cooperation between evacuees and their mobile nodes

Yuki Kasai*, Masahiro Sasabe and Shoji Kasahara

Abstract

When a large-scale disaster occurs, evacuees have to evacuate to safe places quickly. For this purpose, an automatic evacuation guiding scheme based on cooperation between evacuees and their mobile nodes has been proposed. The previous work adopts shortest-distance based route selection and does not consider the impact of traffic congestion caused by evacuation guiding. In this paper, we propose congestion-aware route selection in the automatic evacuation guiding. We first adopt a traffic congestion model where each evacuee's moving speed on a road is determined by the population density of the road and his/her order among evacuees traveling in the same direction. Based on this congestion model, each evacuee's mobile node estimates the cost, i.e., traveling time, of each road in the area. Each mobile node collects information about blocked road segments and positions of other evacuees through communication infrastructures or other mobile nodes. Based on the obtained information, it calculates and selects the smallest-cost route. Through simulation experiments, we show that the congestion-aware route selection can reduce both average and maximum evacuation times compared to the shortest-distance based route selection, especially under highly congested situations. Furthermore, we show that the congestion-aware route selection can work well even under highly damaged situations where only direct wireless communication among mobile nodes is available.

Keywords: automatic evacuation guiding; congestion-aware route selection; mobile nodes

1 Introduction

In the 2011 Great East Japan Earthquake, tremendous damage to communication infrastructures made both fixed and mobile communication networks unavailable for a long time and in wide areas. As a result, it has been reported that evacuees and rescuers could not smoothly collect and distribute important information, e.g., safety information, evacuation information, and government information, even though they carried their own mobile nodes, e.g., cellular phones and smart phones [1]. In such situations, evacuees quickly have to grasp information about safe places and safe routes to those places. Although they can acquire static information, e.g., map and locations of safe places, in usual time, they cannot grasp dynamic information, e.g., damage situations in disaster areas, in advance. To tackle this problem, a scheme has been proposed that enables automatic evacuation guiding based on implicit interactions between evacuees and their mobile nodes [2]. In the automatic evacuation guiding scheme, the mobile node of an evacuee first calculates and presents an evacuation route, i.e., recommended route, to him/her. At the same time, it also traces his/her actual evacuation route as a trajectory by measuring his/her positions periodically. When it detects difference between the recommended route and the actual evacuation route, it can automatically estimate and record the corresponding blocked road segments. These discovered information can be shared among mobile nodes through direct wireless communication and/or communication via remaining communication infrastructures.

In [2], the performance of the automatic evacuation guiding scheme is evaluated from the viewpoint of average/maximum evacuation time among evacuees, under the situations where the recommended route is given as a shortest path and traffic congestion does not occur. In actual situations, traffic congestion may be caused by evacuation behavior. For example, it has been reported that heavy traffic jam occurred due

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to the disruption of the transportation networks at the metropolitan area of Tokyo, in case of the 2011 Great East Japan Earthquake [3]. Note that the automatic evacuation guiding tends to guide physically close evacuees to the same route, due to the sharing of information about blocked road segments among mobile nodes. Therefore, both the alleviation of traffic congestion and the safety of evacuation become important in the automatic evacuation guiding.

In this paper, we propose congestion-aware route selection in the automatic evacuation guiding. In general, the degree of congestion of a road can be modeled as a function of moving speed or traveling time with the number of people traveling on the road. Inspired by the traffic congestion model [4], we propose a traffic congestion model where each evacuee's moving speed on a road is determined by the population density of the road and his/her order among evacuees traveling in the same direction. Based on this congestion model, each evacuee's mobile node estimates the traveling time of each road in the area by collecting the number of evacuees on each road through direct wireless communication with other mobile nodes and/or a server via remaining communication infrastructures. The congestion-aware route selection selects the smallest-cost route based on the estimated traveling time of each road.

Trough simulation experiments, we examine the effectiveness of the proposed scheme in terms of average/maximum evacuation time. Since the performance of the propose scheme depends on the estimation accuracy of congestion state, which is affected by the communication environments, we evaluate the proposed scheme in two kinds of scenarios: global scenario and local scenario. The global scenario is an ideal case where each mobile node can always grasp the locations of all other nodes via communication infrastructures. On the contrary, in the local scenario, communication infrastructures are unavailable and each mobile node can collect the locations of other nodes only within its direct communication range.

The rest of this paper is organized as follows. Section 2 gives related work. Section 3 describes the automatic evacuation guiding. Section 4 describes the proposed congestion-aware route selection. The simulation results are shown in Section 5. Finally, Section 6 provides conclusions.

2 Related works

Various studies have been done for evacuation support in large-scale disasters and some of them focus on traffic congestion caused by evacuation behavior [2, 3, 5–9]. These are mainly divided into two types: analysis of evacuation behavior based on disaster simulations and field survey [3, 5], and evacuation guiding using information and communication technology [2, 6–9].

In [5], the impact of disruption of railway networks on road networks, e.g., geographical distribution of people, is estimated through railway-network simulation under the assumption that the Tokyo metropolitan earthquake occurs. In [3], evacuation behavior is analyzed by the trip data based on a questionnaire survey of the victims of the 2011 Great East Japan Earthquake. In these studies, it has been reported that traffic congestion caused by the disaster can be alleviated by controlling the timing of returning home among evacuees, e.g., making evacuees stay at their schools and offices.

In [6], the authors propose an evacuation guiding system that calculates evacuation routes with timings to suppress traffic congestion, where evacuees can almost always communicate with others through an ad-hoc network. In [7], the authors propose an evacuation guiding system using a delay tolerant network (DTN) [10]. When evacuees encounter blocked road segments or traffic congestion during their evacuations, they register these information to their mobile nodes and share it with other nodes through wireless communication. The shared information will improve the evacuation movement of evacuees. Since it may be difficult for evacuees to register the information to their mobile nodes in emergent situations, Komatsu et al. propose an automatic evacuation guiding based on implicit cooperation between evacuees and their mobile nodes [2]. Komatsu et al. also propose an information sharing scheme called On-Demand Direct Delivery for the automatic evacuation guiding, which can reduce the network load compared to the existing DTN routing [11]. In this paper, we try to combine congestion-aware route selection with the automatic evacuation guiding.

There have also been studied on congestion alleviation in general road networks [12–14]. Verroios and Kollias propose a congestion-aware route selection method for vehicles, with the help of a ad hoc network [12]. They assume that each vehicle is equipped with a Personal Digital Assistant (PDA). Each vehicle collects the position and speed information of other vehicles within its transmission range and estimates the required time to each segment in the target area. It also shares the estimated traveling time to each segment with other vehicles and dynamically determines a route to its destination based on the information. Lim and Rus propose a probabilistic route selection method to realize user equilibrium (Nash equilibrium) and social optimum in game theory [13]. Each agent in a transportation network has route candidates to its destination as a vector in which each element represents the probability to select. It may have some neighbors, each of which is the other agent that share some roads in their route candidates. Each agent tries to select an appropriate route from the candidates by taking account of the influence of route selection on neighbors.

Congestion-aware route selection schemes can be classified in terms of congestion models and sharing methods of congestion information. There are some kinds of congestion models: a model using cellular automata [6, 7], a model based on the function of traffic volume on each road [9, 13], and a model where moving speed depends o the density of moving objects on each road [4, 15]. In this paper, we propose a congestion model by extending the moving-speed based congestion model [4]. The sharing methods of congestion information can be classified in terms of network architectures. Lim and Rus assume that global information sharing among mobile agents can be achieved by communication infrastructures [13]. There are some studies that assume local information sharing can be achieved by ad hoc networks [6, 12] and DTNs [2, 7]. Since the proposed congestion-aware route selection is conducted over the automatic evacuation guiding [2], we apply the DTN-based information sharing.

In the evacuation, it is rational for each evacuee to select a evacuation route whose expected evacuation time is minimum among those of candidate routes. The phenomenon where each evacuee behaves according to such a rational decision is called selfish routing in game theory [16]. In general, such individually rational decisions of evacuees cannot necessarily result in the social optimum, where the average evacuation time among evacuees is minimized. Lim and Rus reveal which utility function to determine the route of each mobile agent results in the social optimum [13]. Note that they assume that the global information sharing among mobile agents can be achieved as mentioned above. In this paper, the proposed route selection is also a kind of selfish routing but the way of information sharing can vary depending on the communication environments, i.e., communication infrastructures or DTNs.

3 Automatic evacuation guiding system

Since the proposed scheme relies on the automatic evacuation guiding system [2], we give the overview of the system.

$G = (\mathcal{V}, \mathcal{E})$ denotes a graph representing the internal structure of the 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 $K > 0$ evacuees in the region and each of them has a mobile node. $\mathcal{K} = \{1, 2, \ldots, K\}$ denotes the set of all the nodes. Each node $k \in \mathcal{K}$ measures its own locations by using GPS (Global Positioning System) at control intervals of $I_{\mathrm{M}} > 0$.

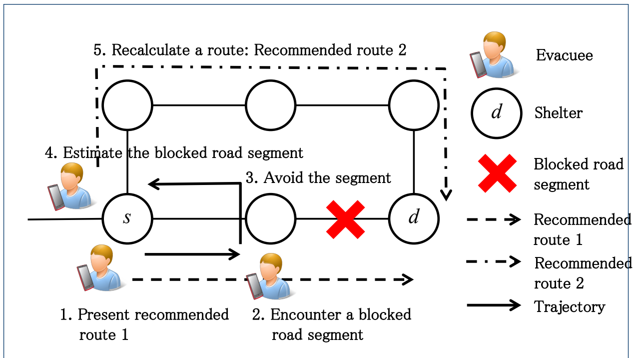

Figure 1 The flow of the automatic evacuation guiding.

Fig. 1 illustrates the flow of guiding one evacuee to a safe place. Note that the evacuee has to pre-install an application for the evacuation guiding into his/her mobile node before disasters occur. The application obtains static information, e.g., the surrounding map of the target region and the location information of the safe places, in usual time. When a disaster occurs, the application is invoked. The application first finds out the nearest safe place d from location s of node k. Then, it calculates evacuation route $\widehat{p}^{k,1}_{s,d}$ and presents him/her the route as a recommended route (Step 1 in Fig. 1).

The evacuee tries to move along the recommended route. When the evacuee encounters a blocked road segment during his/her evacuation along the recommended route $\widehat{p}^{k,1}_{s,d}$ (Step 2 in Fig. 1), he/she will take another route by his/her own judgment (Step 3 in Fig.1). As the same time, the application can trace his/her actual evacuation route as the trajectory by measuring his/her positions periodically with GPS. Thus, the application can detect the road segment $e \in \mathcal{E}$, which yields the difference between the recommended route and the actual evacuation route. The application adds the road segment e to the set $\mathcal{E}^k_{\mathrm{NG}}$ of blocked road segments (Step 4 in Fig. 1). After that, it also recalculates new evacuation route $\widehat{p}^{k,2}_{s,d}$, which does not include blocked road segments $\mathcal{E}^k_{\mathrm{NG}}$, and presents him/her the route (Step 5 in Fig. 1). Evacuation guiding finishes when the evacuee reaches the safe place or the application cannot find out any evacuation route to any safe place. In addition, the mobile node may obtain opportunities to obtain the information about blocked road segments from others, through direct wireless communication with other mobile nodes, e.g., Bluetooth and WiFi-Direct, and/or communication with communication infrastructures, e.g., 3G, 4G, and LTE. Sharing the information about blocked road segments among evacuees will improve their evacuation movements.

4 Congestion-aware route selection

In the previous work [2], the authors assume that the moving speeds of evacuees are constant, independently of traffic congestion. The recommended route is calculated by the shortest-distance based route selection with costs of static road length. When each evacuee selects the shortest path as the recommended route, many evacuees will concentrate on some roads and traffic congestion may occur. In this paper, we propose congestion-aware route selection that can alleviate the traffic congestion. Since the congestion-aware route selection is replaced with the shortest-distance based route selection in the automatic evacuation guiding, it is conducted at control intervals of I_{M}.

In what follows, we first describe a model of traffic congestion on roads. Next, we explain a method of acquiring information for route calculation and the definition of road costs. Finally, we describe the route calculation based on the obtained road costs.

4.1 Congestion model

The degree of congestion on a road is correlated with the number of evacuees passing through that road. In [4, 15], the relationship between the moving speed v [m/s] of pedestrians and population density κ [1/m^2] on a road is given by

$$v = 1.2 - 0.25\kappa. \tag{1}$$

In this paper, we extend this congestion model by taking account of the order of evacuee on a road. It is natural to assume that the congestion degree is different among evacuees on a road, depending on their positions on that road: the evacuee at the head of the road is not affected by other evacuees on that road while that at the tail of that road is affected by all other evacuees on that road.

Fig. 2 illustrates our congestion model. In Fig. 2 (a), there is a group of four evacuees moving in the same direction on a road, and i-th evacuee is moving at speed v_i $(i = 1, \ldots, 4)$. v_i is determined by (1) with the number of evacuees who are moving ahead of i-th evacuee, i.e., $i-1$, and the area of that road. Fig. 2 (b) illustrates the situation just after evacuee A leaves the road. At this moment, the moving speeds of the remaining evacuees B, C, and D change as shown in Fig. (b). In what follows, we describe the congestion-aware route selection based on this congestion model.

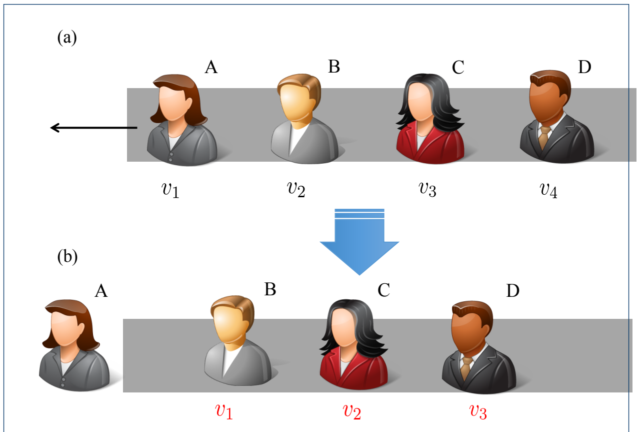

Figure 2 Evacuees' moving speed model: (a) A situation where four evacuees, A, B, C, and D, move in the same direction on a road and (b) the situation just after evacuee A leaves the road.

4.2 Information retrieval of blocked road segments and evacuees' locations

In our congestion model, mobile node k needs to grasp the degree of congestion of each road segment, i.e., the number of evacuees. In addition, mobile node k also requires to grasp blocked road segments, which will be used in the automatic evacuation guiding scheme. Therefore, mobile node k tries to retrieve the information about block road segments and the current position from other mobile node at control intervals of I_{M} through communication infrastructure with transmission range R_{I}, e.g., cellular network and wireless LAN, or direct wireless communication with transmission range R_{D}, e.g., Wi-Fi Direct and Bluetooth.

In this paper, we assume that two extreme scenarios: global scenario and local scenario. In the global scenario, the communication infrastructure is sufficiently deployed and each mobile node can communicate with all other nodes at control intervals of I_{M}. In the local scenario, the communication infrastructure is fully damaged by the disaster and each mobile node can communicate with other node only through the direct wireless communication. Note that the range of flooding messages is limited to one hop in the local scenario, in order to alleviate the load on communication networks. We will show this limitation does not much affect the evacuation guiding with appropriate value of transmission range R_{D} (See Sec. 5.5).

Fig. 3 illustrates the overview of information retrieval in global scenario and local scenario. In this figure, evacuee k moves on road segment e_1 from s to a and the number in each circle represents the moving order of the corresponding evacuee. As mentioned above, the movement speed of evacuee is determined by the moving order among evacuees traveling on the

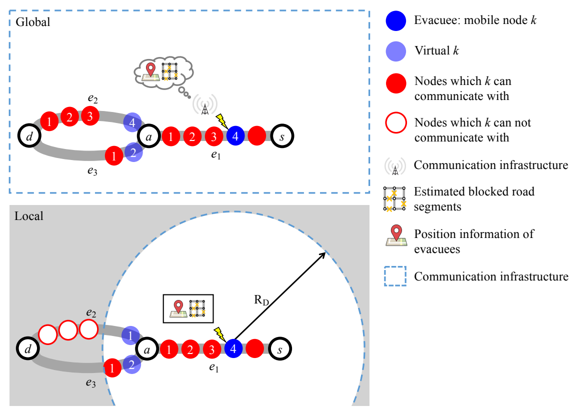

Figure 3 Information retrieval of congestion-aware route selection.

same road. Therefore, mobile node k requires the information about its moving order on each road segment when it travels the corresponding road segment. In the global scenario (the upside of Fig. 3), mobile node k can know the positions of all other nodes. On the contrary, mobile node k can know the positions of other nodes in transmission range of R_{D} in the local scenario (the downside of Fig. 3).

4.3 Road cost model

Let $o_{e,k}$ denote the moving order of evacuee k on road segment e. As for the road segment on which evacuee k travels, mobile node k can estimate $o_{e,k}$ directly from the obtained information, e.g., $o_{e_1,k} = 4$ in Fig. 3. As for the other road segment e, it is difficult for k to estimate the number of evacuees traveling on e when k arrives at e. Mobile node k estimates its moving order on e, $o_{e,k}$, as n_e+1, where n_e is the number of evacuees that currently travels on e. For example, $o_{e_2,k} = 3+1 = 4$ and $o_{e_3,k} = 1+1 = 2$ in the global scenario of Fig. 3, $o_{e_2,k} = 0+1 = 1$ and $o_{e_3,k} = 1+1 = 2$ in the local scenario in Fig. 3.

We should note here that $o_{e,k}$ will change as time passes. As mentioned in Sec. 4.2, each mobile node tries to retrieve the positions of other mobile nodes at control intervals of I_{M}. To simplify the calculation, we define road e's cost for mobile node k, $c_{e,k}$, as follows:

$$c_{e,k} = \frac{l_e}{\frac{\sum_{i=1}^{o_{e,k}} v_i}{o_{e,k}}} = \frac{o_{e,k} l_e}{\sum_{i=1}^{o_{e,k}} v_i}, \tag{2}$$

where l_e is the length of road e. (2) indicates the average traveling time of road e among evacuee k and his/her preceding evacuees.

4.4 Route calculation

Based on each road cost estimated by (1), mobile node $k \in \mathcal{K}$ selects route $\widehat{p}^k_{s,d}$ with the smallest total cost among set $\mathcal{P}^k_{s,d}$ of route candidates from current location $s \in \mathcal{V}$ to destination $d \in \mathcal{V}$, using existing graph search algorithms, e.g., Dijkstra's algorithm,

$$\widehat{p}^k_{s,d} = \mathop{\arg\min}_{p \in \mathcal{P}^k_{s,d}} \sum_{\forall e \in p} c_{e,k}. \tag{3}$$

For example, $\mathcal{P}^k_{s,d}$ is $\{\{e_1, e_2\}, \{e_1, e_3\}\}$ in Fig. 3. Suppose $l_{e_2} = l_{e_3}$. In the global (resp. local) scenario, mobile node k selects route $\{e_1, e_3\}$ (resp. $\{e_1, e_2\}$) because $o_{e_3,k} < o_{e_2,k}$ (resp. $o_{e_2,k} < o_{e_3,k}$).

When mobile node $k \in \mathcal{K}$ starts its evacuation, it calculates the first route. At control intervals of I_{M}, it also conducts the route calculation when at least one of the following conditions is satisfied.

(C1) When mobile node k newly obtains information about a block road segment by the automatic evacuation guiding scheme.

(C2) When the moving speed of mobile node k becomes slower than threshold $\theta_{\mathrm{V}} \geq 0$, due to the traffic congestion.

Condition (C1) ensures that mobile node k can avoid blocked road segment as in the existing automatic evacuation guiding. Note that not only the information about blocked road segments but also the latest information about each road cost will improve the evacuation route.

In addition to condition (C1), the congestion-aware route selection also aims to adapt to change of traffic condition if needed. The performance of congestion-aware route selection depends on the estimation accuracy of each road's cost given by (2). In the global scenario, each mobile node can obtain the number of evacuees on each road, regardless of their locations. However, it is not necessarily for each mobile node to grasp the congestion states of distant roads because they will change according to evacuees' movement. On the contrary, the estimated congestion states of near roads will not almost change when the evacuee arrive at them. Taking account of this characteristic, mobile node k evaluates the quality of current evacuation route based on that of current road segment, i.e., current moving speed, as in condition (C2).

This characteristic of estimation accuracy also indicates that the shortsighted estimation in the local scenario will be competitive with the farsighted estimation in the global scenario, depending on the transmission range R_{D} of direct wireless communication. We should also note here that the congestion-aware route selection tends to allocates evacuees to different

Figure 4 The map of Nagoya city.

Table 1 Information of the map of Nagoya city.

Map information	
Map size	$3,500$ [m] $\times$ $2,300$ [m]
Number of vertexes	$3,972$
Number of directed edges	$7,918$

routes, thus it will reduce the opportunities of information sharing among mobile nodes in the local scenario. Taking account of these points, we will examine how the congestion-aware route selection can work well even in the local scenario in Sec. 5.

5 Simulation experiments

In this section, we show the effectiveness of the congestion-aware route selection through simulation experiments.

5.1 Simulation model

We developed a simulator based on The ONE [17]. We used the map of southwest area of Nagoya station in Japan (Fig. 4). Table 1 shows the size and graph structure of the map. In case of Nagoya city, some useful information is available, i.e., population, area of road network, location of safe place, and road blockage probability.

The proposed congestion model given by (1) depends on population density on each road. The population of Nagoya city is about 2.3 million and the road area in the city is about 50 [km^2], according to the population and road statistics information [18]. Thus, the population density on the road network is 0.046 [1/m^2]. Note that this population only includes the residents and is called the nighttime population. In the daytime, more people, e.g., business people, students, and shoppers, move into the urban areas. The proportion of the daytime population per 100 persons of nighttime population is called the ratio of daytime population to nighttime population, r. The average and maximum of r is 113.5 and 373.1 in Nagoya city, respectively [19]. In what follows, we evaluate the impact of degree of congestion by changing r in the range of $[100, 400]$.

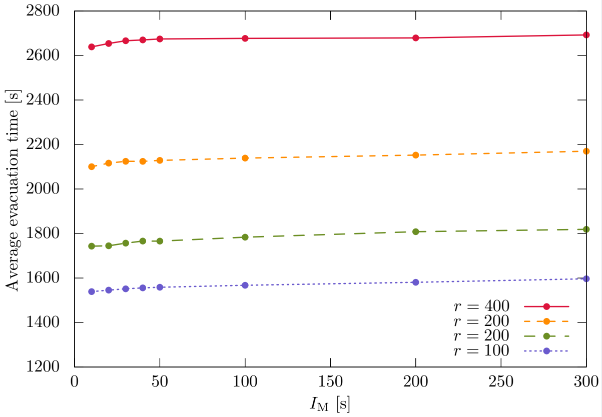

Figure 5 Control interval I_{M} vs. average evacuation time (global scenario).

As for the disaster scenario, we set part of roads to be blocked, i.e., red lines in Fig. 4, according to the road blockage probabilities. Nagoya city has been evaluating the regional risks, e.g., road blockage probabilities, caused by future large-scale disasters such as Nankai Trough Earthquake [20]. The road blockage probability is an estimated probability that the corresponding road is blocked due to collapse of buildings along the road under a certain disaster. It is calculated based on the degree of collapse and height of each building along the road, and the width of the road.

We assume that each evacuee has one mobile node and starts his/her evacuation from a random point on the map. We set a safe place to the actual location, i.e., green circle in Fig. 4). The simulation time is set to be 10,000 seconds. When the simulation starts, a disaster occurs and each evacuee starts evacuation. We set threshold of route recalculation θ_{V} to be 0 [m/s]. As for the communication environments, we used the global scenario and the local scenario described in Sec. 4.2.

We evaluate the proposed scheme in terms of average evacuation time T_{avg}, maximum evacuation time T_{max}, and the evacuation ratio. Note that the evacuation time of each evacuee is defined as the time interval from his/her evacuation start to evacuation completion. The evacuation ratio is defined as the ratio of evacuees who arrive at the safe place to all evacuees. The following results are the average of 70 independent simulation results.

5.2 Sensitivity to control interval I_{M}

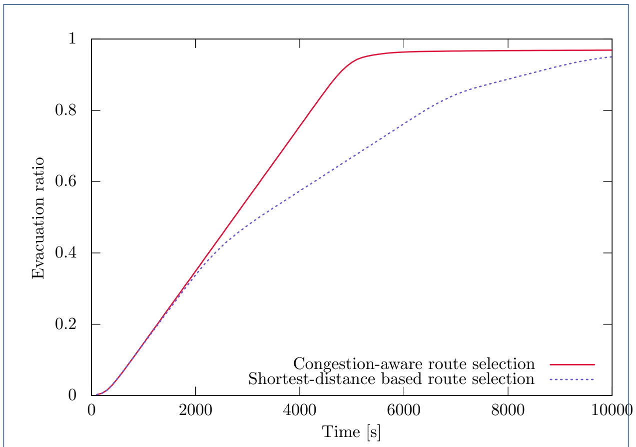

Figure 6 Transition of evacuation ratio (global scenario).

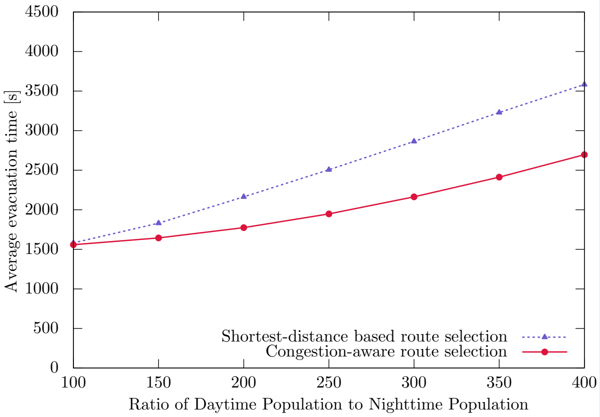

Figure 7 The ratio of daytime population to nighttime population vs. average evacuation time (global scenario).

The performance of congestion-aware route selection depends on control interval I_{M}. Small I_{M} can achieve quick response to traffic congestion but will increase both computing and networking overhead. Fig. 5 illustrates the relationship between I_{M} and average evacuation time in case of global scenario. Regardless of the ratio r of daytime population to nighttime population, we observe that the average evacuation time gradually increases with I_{M}, due to delays in detecting and avoiding congestion. In what follows, we set I_{M} to be 50 [s] by taking account of the balance between average evacuation time and overhead.

5.3 Effect of congestion-aware route selection

In this section, we show the performance comparison between congestion-aware route selection and shortest-distance based route selection in the global scenario.

Fig. 6 represents the transition of evacuation ratio for congestion-aware route selection and shortest-distance based route selection when ratio of daytime population to nighttime population, r, is set to be 400. We observe that the congestion-aware route selection can increase the evacuation ratio faster than the shortest-distance based route selection. The average evacuation time becomes $2,720$ [s] for the congestion-aware route selection and $3,599$ [s] for the shortest-distance based route selection. Thus, the improvement ratio of average evacuation time is about 24 %. On the contrary, the maximum evacuation time becomes $5,846$ [s] for the congestion-aware route selection and $9,644$ [s] for the shortest-distance based route selection. The improvement ratio of maximum evacuation time is about 39 %.

We also find that both route selections show similar evacuation ratio at the early stage of evacuation but the congestion-aware route selection achieves much higher evacuation ratio than the shortest-distance based route selection during the remaining period. Since each evacuee starts from various points in the area, concentration of evacuees on specific roads is unlikely to occur at the early stage of evacuation. As a result, the congestion-aware route selection also tends to apply the shortest path. As time passes, the number of evacuees approaching the safe place gradually increases. As a result, heavy traffic congestion occurs in the case of shortest-distance based route selection. On the contrary, the congestion-aware route selection can alleviate the traffic congestion.

5.4 Impact of congestion degree

In this section, we evaluate the impact of congestion degree on both route selections in terms of average/maximum evacuation time in the global scenario. Fig. 7 illustrates the relationship between ratio r of daytime to nighttime population and average evacuation time. We first observe that there is almost no difference between the results of two route selections when r is small, e.g., $r = 100$. When congestion degree r increases, the effectiveness of congestion-aware route selection increases.

Fig. 8 shows the relationship between ratio r of daytime population to nighttime population and maximum evacuation time. As in case of average evacuation time, we observe that there is almost no difference between the results of two route selections when $r = 100$. Comparing Fig. 8 with 7, we find that the congestion-aware route selection can much improve the maximum evacuation time when r increases.

5.5 Impact of communication environments

In this section, we evaluate the impact of communication environments on average/maximum evacuation time for two route selections.

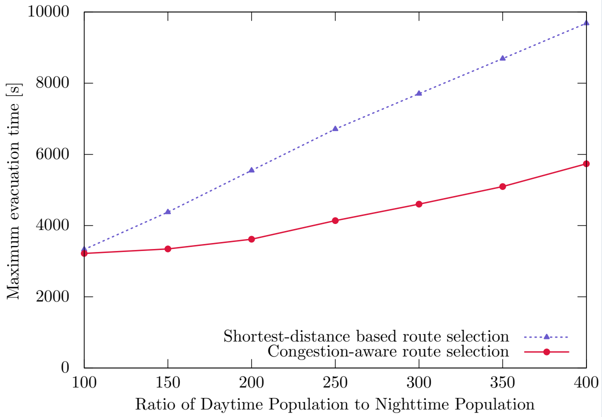

Figure 8 The ratio of daytime population to nighttime population vs. maximum evacuation time (global scenario).

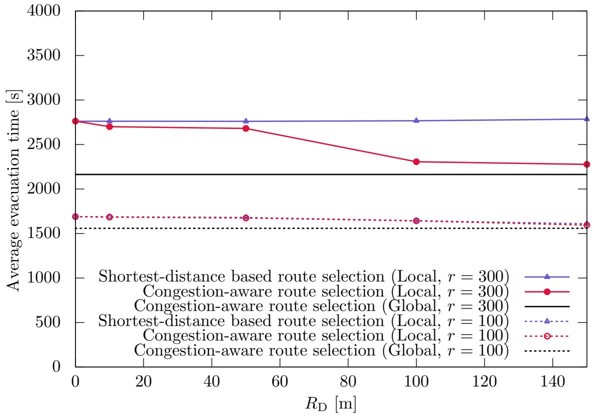

Figure 9 Transmission range vs. average evacuation time.

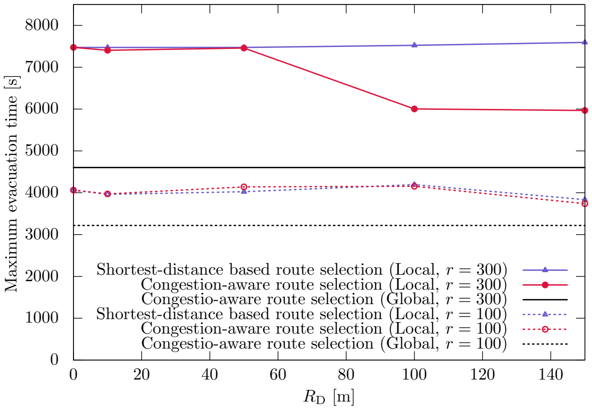

Figure 10 Transmission range vs. maximum evacuation time.

Fig. 9 (resp. Fig. 10) illustrates the relationship between transmission range R_D of direct wireless communication and average (resp. maximum) evacuation time, when ratio r of daytime population to nighttime population is set to be 100 and 300. For comparison purpose, we also show the average (resp. maximum) evacuation time of congestion-aware route selection in case of global scenario in Fig. 9 (resp. Fig. 10).

First, we focus on the results of local scenario. We observe that there is almost no difference between two route selections when $r = 100$. In addition, transmission range R_D does not much affect the average/maximum evacuation time, regardless of route selection. This is because traffic congestion rarely occurs due to the low congestion degree, as mentioned in Sec. 5.3.

On the contrary, when the congestion degree increase, i.e., $r = 300$, we observer that the congestion-aware route selection (resp. the shortest-distance based route selection) can (resp. not) improve the average/maximum evacuation time with increase of R_D. In the automatic evacuation guiding, regardless of the route selection, the wide transmission range will results in increase of information retrieval of blocked road segments. As for the shortest-distance based route selection, each evacuee selects the shortest-distance route, thus route concentration among evacuees frequently occurs. When the congestion degree increases, the impact of traffic congestion dominates the average/maximum evacuation time in case of shortest-distance based route selection.

Focusing on the congestion-aware route selection in case of $r = 300$, we observe that the average/maximum evacuation time is improved with increase of transmission range. In particular, we find that large improvement occurs when $R_D = 100$. This indicates that Bluetooth whose transmission range is dozens of meters is not sufficient but Wi-Fi Direct whose transmission range can be one hundred meter is sufficient. In case of the road network in Fig. 4, the average road length is about 60 [m]. Thus, the congestion-aware route selection can work well even if each mobile node only grasps the number of evacuees on the current road and next road candidates. We also find that the average evacuation time in the local scenario with $R_D = 100$ is competitive with that in the global scenario.

These results indicate that autonomous and decentralized congestion alleviation can be realized even in the poor communication environments where communication infrastructures are unavailable and each mobile node can communicate with other nodes only within its direct communication range.

6 Conclusion

In this paper, we consider the problem of traffic congestion caused by the automatic evacuation guiding system. We first developed a traffic congestion model where an evacuee's moving speed on a road is determined based on the population density and his/her moving order among evacuees on that road. Next, we proposed the congestion-aware route selection where each evacuees selects an evacuation route with the minimum cost based on the cost model.

Through several simulation experiments, we showed that (1) the congestion-aware route selection works better than the shortest-distance based route selection at the middle and late stage of evacuation by alleviating the traffic congestion around the safe place, (2) the effect of congestion-aware route selection becomes high with increase of congestion degree, and (3) the congestion-aware route selection with local information sharing through direct wireless communications among mobile nodes can be competitive with that with global information sharing through communication infrastructures under the realistic transmission range of direct wireless communication, e.g., $R_{\mathrm{D}} = 100$.

Competing interests

The authors declare that they have no competing interests.

Author's contributions

The authors have contributed to this paper and all authors read and approved the final manuscript.

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