Effect of Aggressive Evacuation Behavior Associated with Information-Sharing Using a DTN on Evacuation Time

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***Abstract*—In a large-scale disaster, providing evacuees with appropriate evacuation routes based on the location of closed road segments and shelters is expected to be useful for rapid evacuation. To enable information-sharing even when communication infrastructure is unavailable, Yahara et al. have proposed a disaster information-sharing system using a heterogeneous wireless DTN, combining short-range broadband wireless communications with long-range narrowband wireless communications. In their system, the locations of closed road segments are shared so that evacuees can avoid the closed road segments. However, the system does not distribute information about congestion. Thus, many evacuees may choose the same route and experience a long evacuation time. The system should provide evacuees not only the location of closed road segments but also evacuation routes selected based on the closed road segments and the congestion of road segments to enable more efficient evacuation. On the other hand, there is concern that evacuees who have received a recommended evacuation route may act against the movement of other evacuees who have not received the recommended route, causing congestion and increasing the evacuation time. We investigated the impact of providing recommended evacuation routes selected based on the road congestion estimated from wireless communication between evacuees and fixed nodes and the aggressive behavior of evacuees who have received a recommended evacuation route through simulations. The simulation results reveal that providing evacuation routes selected based on the closed road segments and the road congestion is effective in shortening the evacuation time; also, the aggressive behavior of evacuees who have received a recommended evacuation route contributes to arranging the evacuation flows so that they can move smoothly when the road congestion is high.**

***Index Terms*—DTN, Disaster, Evacuation, Aggressive, Simulation**

I. Introduction

Japan is one of the most disaster-prone countries in the world and is at risk of various natural disasters such as typhoons and earthquakes. In particular, the occurrence of large-scale disasters, such as the Nankai Trough Earthquake, is a growing concern, and preparedness for such disasters is becoming increasingly important. In a disaster, evacuation routes and means of transportation are limited due to tsunamis, floods, etc. in the affected areas. Therefore, it is necessary to appropriately share information about evacuation routes and damaged areas among evacuees and disaster management organizations to enable rapid evacuation. During a disaster, the communication infrastructure may be unavailable due to power outages and the breakdown of many cell phone base stations. Such damage to communication infrastructure may make it difficult to share information using the same methods as in ordinary times. For example, in the Great East Japan Earthquake in 2011, approximately 8.5 million homes lost power, and disaster victims could not use telecommunication media for several days. 1.9 million lines, or more than 50% of the disaster area's fixed lines, were damaged, and 29,000 cell phone base stations were shut down or damaged [1] [2].

Since the Great East Japan Earthquake, there have been many studies on the effectiveness of information-sharing using DTN in situations where existing communication infrastructure is unavailable. Owada et al. have proposed a method for providing evacuation assistance information to evacuees using a mesh network of multiple access points called NerveNet [3]. NerveNet can immediately switch to another communication link to ensure communication even if some communication links fail. Nishiyama et al. have proposed "Smartphone de Relay" [4], which uses direct communication between mobile devices using Bluetooth to share information, such as pictures of a disaster site and text messages regarding the degree of damage to buildings, etc. In the system, when there is no device in the vicinity of a device that can communicate with it, data are physically transported with the device. They are shared when the device is in the vicinity of another device.

Our research team has proposed an evacuation assistance information-sharing system using a heterogeneous wireless DTN [5], which uses both short-range broadband radio communication, such as Wi-Fi, and long-range narrowband radio communication, such as LoRA and Digital Convenience Radio (DCR), to compensate the poor connectivity only with short-range broadband radio when the mobile devices' density is low. The authors conducted simulations and confirmed that sharing the location of closed road segments with other evacuees so that they can take a detour using such a network is effective in shortening the evacuation time. However, it was also observed that evacuees are sometimes concentrated in certain routes because many evacuees take the same route to avoid closed road segments. In this paper, we extend the system proposed in [5] to provide evacuees with recommended evacuation routes based on the degree of congestion, in addition to sharing the location of closed road segments. Providing an evacuee with recommended evacuation routes may change his/her behavior. For example, if he/she is in the flow of going east and receives a recommended route that guides evacuees to the west, he/she needs to act aggressively to move against others' move. In this paper, we developed a simulation model to treat such behavior of evacuees to investigate the extended information-sharing system in a realistic environment.

The contributions of this paper are summarized as follows.

1) We designed a framework that enables smooth evacuation guidance by deriving recommended evacuation routes based on the road congestion estimated from the number of beacons emitted by mobile devices and distributing them via a hybrid DTN.
2) We designed a mobility simulator that models the aggressive behavior of evacuees who follow a recommended route against surrounding evacuees' mobility.
3) We conducted simulations of disaster evacuation, dealing with both the change in communication availability at a DTN, which changes with movement, and the change in evacuee behavior receiving information on the closed road segments and a recommended evacuation route via the DTN.
4) We confirmed that providing recommended evacuation routes effectively reduces the time to evacuation, especially when evacuee density is high. We also confirmed that aggressive evacuees' behavior contributes to forming two-way evacuation lanes and smoothing their mobility.

The rest of the paper is organized as follows: Section II gives the overview and the issues of disaster information-sharing systems using a heterogeneous wireless DTN. In Section III, we propose a method of estimating the degree of congestion based on information shared in the heterogeneous wireless DTN and providing recommended evacuation routes to evacuees. Section IV details the simulation model. Section V evaluates the effect of the proposed information-sharing system. Finally, Section VI concludes the paper.

II. Evacuation Assistance Information-Sharing System Using a Heterogeneous Wireless DTN

A. System overview

Fig. 1 shows an overview of a disaster information-sharing system using a heterogeneous wireless DTN. This system consists of mobile devices carried by evacuees and fixed relay nodes installed at buildings of disaster management agencies and roadsides. The mobile devices are equipped with short-range broadband wireless communication functions, and the fixed relay nodes are equipped with radio communication devices of both short-range broadband and long-range narrowband. Evacuees who find a closed road segment broadcast the location to surrounding evacuees and fixed relay nodes. The delivering of recommended evacuation routes is a newly introducing in this paper and is explained in detail in Section III.

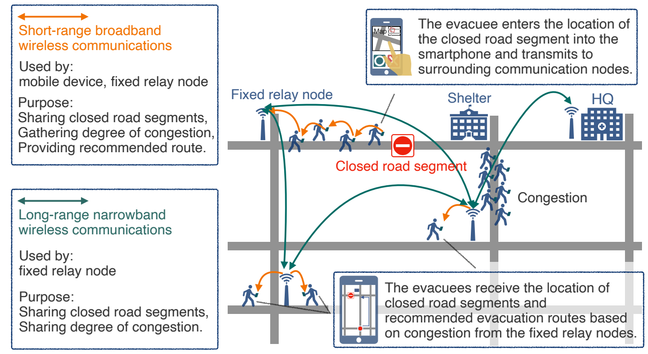


Fig. 1. A disaster information-sharing system using a heterogeneous wireless DTN.

B. Challenges when sharing evacuation support information

In the previous system [5], only information on closed road segments is shared between evacuees and fixed relay nodes. Evacuees who have obtained such information take the shortest route and avoid closed road segments without considering congestion. That is, sharing only the information on closed road segments will lead to long evacuation times. Therefore, if not only the information on closed road segments but also on the congestion of the evacuation route is shared, the concentration of evacuees on a specific route will be mitigated.

C. Aggressive behavior that goes against the flow of surrounding evacuees

Evacuees who have obtained information on a recommended evacuation route may be required to move against the flow of the surrounding crowd or change direction to change routes. Under crowded conditions, they may not always be able to move in the direction they desire. The characteristics of the evacuees, the density of the evacuees on the road, and the flow of movement of other evacuees will have an impact on movement. Therefore, a mobility model that can take into account the differences in human movement along and against the flow of people is necessary for simulation. We designed aggressive behavior that goes against the flow of surrounding evacuees by following the path recommended by the system.

III. Recommendation of Evacuation Routes Based on Congestion

In this section, we extend Yahara et al.'s evacuation assistance system using a heterogeneous wireless DTN [5] to solve the concentration of evacuees on a specific route. In the assumed the heterogeneous wireless DTN, the following three points need to be considered.

- How to estimate the degree of congestion for each road segment.
- How to select desirable routes to shelters based on the estimated degree of congestion.
- How to distribute the selected routes to evacuees.

A. How to estimate the degree of congestion

We use plain strategy to estimate the degree of congestion, mobile devices carried by evacuees broadcast the current position obtained by GNSS (Global Navigation Satellite Systems) at a regular interval via short-range wireless communication. Each fixed relay node counts beacons received from evacuees for a certain period of time and then shares the number of beacons with other fixed relay nodes via long-range wireless communication. By using the shared numbers of received beacons, fixed relay nodes estimate the number of evacuees on each road segment. Based on these data, fixed relay nodes can estimate the time required to move from any position in the area covered by the system to a shelter.

B. How to select recommended evacuation routes

An evacuation route recommended for an evacuee should be one with the shortest evacuation time. However, it is difficult to accurately estimate the evacuation time for each evacuee. When estimating the evacuation time, it is necessary to take into account the dynamically changing walking speed of all evacuees, which depends on age, gender, aggressiveness, road width, road condition, etc.

In this paper, we assume that each fixed relay node uses the following naive strategy to select the best evacuation route from itself to one shelter (We assume only one shelter exists).

1) The fixed relay node selects the top three routes with the shortest Euclidean distance along the road from the fixed relay node to the shelter, considering the existence of closed road segments.
2) The fixed relay node calculates the sum of beacons received from each road segment along each of the top three routes. The route with the smallest number of beacons is selected as the best route.
3) If multiple different fixed relay nodes have counted the number of beacons for a road segment, the sum of the counted numbers is treated as the estimated number of evacuees on the road segment because we assume that the coverage of the short-range wireless communication of each fixed relay node does not overlap with ones of other fixed relay nodes.

C. How to distribute the recommended evacuation routes

Generally, evacuation routes selected by fixed relay nodes should be provided to all evacuees quickly. There are many strategies to distribute information to all nodes in a DTN, such as epidemic routing [6], spray and wait [7], etc. We need to take into account that the best evacuation route for each evacuee is different from one for others. That is, spreading one route information to all evacuees does not make sense. If many evacuees follow one route, the route will be heavily congested.

In this paper, we assume the following simple strategy: a fixed relay node delivers route information to evacuees who move near the fixed relay node. Each fixed relay node selects the best route from its position to one shelter and broadcasts the route information via short-range wireless communication. Thus, evacuees in the coverage of the fixed relay node's short-range wireless communication can receive the route information and take the route.

IV. Simulation model

In order to evaluate the effect of providing evacuation routes based on information exchanged via heterogeneous wireless DTN, we developed a simulation model. The simulation model covers spreading of the information about closed road segments, beacons for estimating road congestion, broadcast of a recommended evacuation route from fixed relay nodes, and the behavior of evacuees. In particular, we developed a model of the aggressive behavior of evacuees who have received a recommended evacuation route.

The simulation model is based on a two-dimensional cellular automaton model, in which roads are represented as a set of continuous cells. Each road and intersection is assigned an ID. Each evacuee and fixed relay node has a map of the target area. The evacuees know their current location and the location of the shelter and can select the shortest route from their current location to the shelter based on the number of cells. If each evacuee has received information about closed road segments, he/she selects the shortest route by avoiding the closed road segments.

A. Communication Model

We assume the wireless communication range is expressed in 4-neighborhood distance. Let R_{short} and R_{long} be the range of short-range broadband communication and long-range narrowband communication, respectively. When a communication node transmits information using short-range broadband wireless communication, the information is sent to all communication nodes that exist within R_{short} cells from itself. For long-range narrowband wireless communication, which is used only between fixed relay nodes, information is sent from the source fixed relay node to all fixed relay nodes that exist within R_{long} cells. At each time step, each evacuee sends packets with the ID of the road segment or intersection where it is staying and location information on the closed road segment to the surrounding communication nodes.

1) Sharing of information on closed road segments: When an evacuee encounters a closed road segment, the evacuee sends the road ID to all nodes within R_{short}. A node (an evacuee or a fixed relay node) that obtains the road ID of the closed road segment sends the ID to all nodes existing within R_{short} during the same time step. In addition to transmitting the road IDs of the closed road segment to the surrounding evacuees using short-range broadband wireless communication every one time step, the fixed relay node shares the information of the closed road segment with other fixed relay nodes within R_{long} using long-range narrowband wireless communication every ten time steps.

2) Sending a recommended evacuation route: At every one time step, each evacuee broadcasts a beacon packet including its current road ID to nodes within R_{short}. This ID is used to estimate the congestion of the road segment. Fixed relay nodes are installed in cells adjacent to intersections so that they can receive packets with the IDs of adjacent road segments and intersections. Each fixed relay node counts the number of beacon packets with the IDs of each road segment and intersection that it receives during 10 time steps. Every 10 time steps, each fixed relay node shares the number of received packets per adjacent road and intersection with other fixed relay nodes in R_{long}.

Each fixed relay node selects three routes as candidates with short Euclidean distance along the road from the fixed relay node to the shelter. The fixed relay node sums up the number of received packets counted at roads and intersections along the candidate routes and the routes with the lowest total number of packets among the candidate routes from its location to the shelter. This recommended evacuation route information is sent to evacuees within R_{short} from the specific fixed relay node every 10 time steps.

B. Aggressive evacuation behavior model

As evacuees acquire information on closed road segments or a recommended evacuation route, he/she may act against the flow of surrounding evacuees. We introduce an evacuee's behavior model supporting aggressive behavior when obtaining such information and normal behavior when he/she has not obtained such information. At each time step, each evacuee tries to find the shortest route to the shelter based on the information he/she has. The evacuee makes a probabilistic decision to take action (move up, down, left, or right to a neighboring cell, or not move) based on the route he/she wants to take and the condition of the surrounding cells.

The probability of each evacuee's movement in each direction is calculated considering the direction of movement of evacuees in the adjacent cells, the evacuee's aggressiveness, and the distance to the destination. Let C_i be the set of four neighboring cells of cell i. $p_{i,j}$, the probability of movement of an evacuee staying in cell i to cell $j \in C_i$, is calculated as follows.

$$p_{i,j} = \frac{S_{i,j}}{\sum_{k \in C_i} S_{i,k}}, \tag{1}$$

$$S_{i,j} = \exp\left(\Delta f_{i,j}\right) \hat{N}_j \exp(F_{i,j}), \tag{2}$$

where $S_{i,j}$ represents the strength of movement from cell i to cell j. $\Delta f_{i,j}$, $\hat{N}_j$, and $F_{i,j}$ are the proximity to the destination, the number of new evacuees that cell j can accept, and the strength of movement affected by the flow of evacuees in cell i, respectively.

1) $\Delta f_{i,j}$: proximity to destination: When an evacuee is moving from cell i to j, the proximity to the destination is calculated as the difference between the distance from i to the destination and one from j. Let the distances be f_i and f_j, $\Delta f_{i,j}$ is calculated as follows.

$$\Delta f_{i,j} = f_i - f_j \tag{3}$$

When $\Delta f_{i,j}$ is positive, cell j is closer to the destination than i, and this value works for the evacuee to approach the destination.

2) $\hat{N}_j$: the number of new evacuees that cell j can accept: In general cellular automaton models, the maximum number of people in a cell, is constant, but we assume that this number can change in our model, which treats aggressiveness of evacuee who obtains information regarding a better evacuation route. This model allows that a cell can accept more evacuees if the evacuee is aggressive.

Let $N_{\max}$ be the maximum number of evacuees that a cell can accept when all evacuees who want to enter the cell do not have information regarding a better evacuation route, i.e., they all are not aggressive. Then, the number of evacuees that cell i can accept, $\hat{N}_j$, is calculated as follows.

$$\hat{N}_j = \begin{cases} N_{\max} - N_j & \text{(The evacuee is not aggressive.)} \\ N_{\max} - N_j + N_{\text{add}} & \text{(The evacuee is aggressive.),} \end{cases}$$

where N_j is the number of evacuees in cell j, and N_{add} is the additional number of aggressive evacuees that j can accept.

3) $F_{i,j}$: strength of movement affected by the flow of evacuees in cell i: This strength is calculated from the aggressiveness of the evacuee and the flow of evacuees in cell j. Let N_r^j denote the number of evacuees in cell j that have moved in the opposite direction of the ego evacuee in the previous time step. Similarly, let N_c^j, N_s^j denote the number of evacuees in cell j that have moved in the intersecting direction of the ego evacuee and the number of evacuees in cell j that have stayed in the previous time step, respectively. Assuming E is the aggressiveness of the evacuee, $F_{i,j}$ is calculated as follows.

$$F_{i,j} = E - W_r N_r^j - W_c N_c^j - W_s N_s^j, \tag{4}$$

where W_r, W_c, and W_s are weights that represent the degree to which N_r^j, N_c^j, and N_s^j hinder the movement of the evacuee, respectively. We assume that $0 \le W_s \le W_c \le W_r \le 1$.

V. SIMULATION

We conducted simulations to evaluate the effectiveness of the proposed evacuation assistant method and aggressive evacuees' behavior using the three scenarios shown in Table I.

A. Simulation set up

We use a map shown in Fig. 2 for simulations. Each road and intersection is assigned an ID. The simulation parameters are shown in Table II. The cell size was set to 2 m square. The maximum cell capacity $N_{\max}$ was set to 4 because the pedestrian density was set to 1 person/m^2. The walking speed of the evacuees was set to 1 m/sec., referring to the speed used in simulations in [5], and the time per time step was set to 2 sec. Thus, each evacuee could move up to one cell in one time step. The simulation time was set to 22 min. (660 time steps). This time was set concerning the expected maximum tsunami arrival time in Hamamatsu City, Japan, in case of the Nankai Trough Earthquake [8]. The maximum tsunami arrival time is defined as the time from the occurrence of an earthquake to arrival of the maximum tsunami.

TABLE I
SIMULATION SCENARIOS

Scenarios	Send closed road segments	Send recommended evacuation routes
i) No information-sharing	-	-
ii) Only closed road segments	√	-
iii) Closed road segments and recommended routes (Proposed)	√	√

*With/without aggressive evacuees' behavior for each scenario

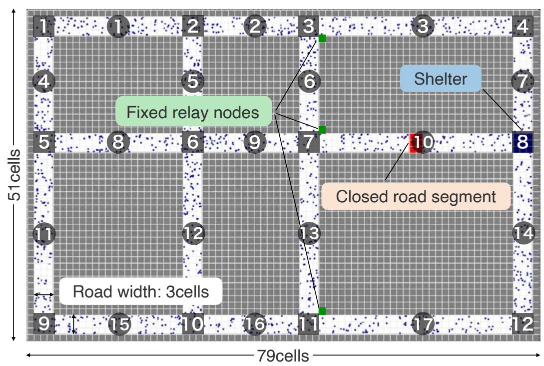
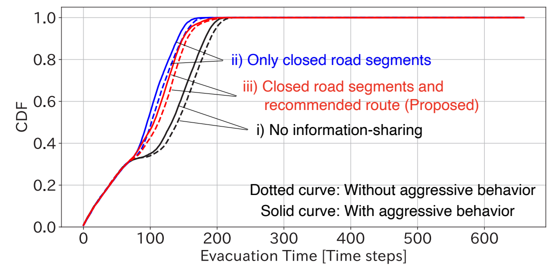


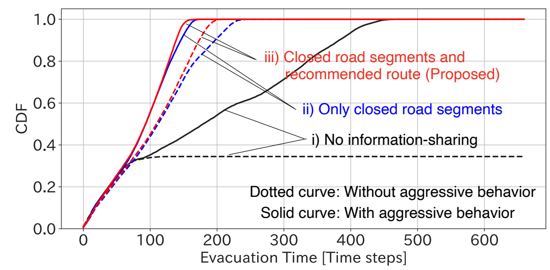
Fig. 2. Simulation map

TABLE II
SIMULATION PARAMETERS

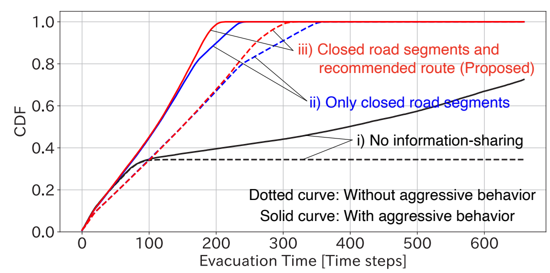
Parameters	Value
Cell size	2.0 m × 2.0 m
Maximum cell capacity $N_{\max}$	4
Additional capacity N_{add}	1
Initial location of evacuees	Uniformly distributed random number
Total number of evacuees	100–1600
Evacuee movement speed	1.0 m/sec.
Aggressiveness E	Random number between 0 and 1
(W_s, W_c, W_r)	$(0.1, 0.3, 0.5)$
Communication range of short-range broadbandR_{short}	3 cells
Communication range of long-range narrowbandR_{long}	100 cells
Time per time step	2.0 sec.
Simulation time	22 min. (660 time steps)



(a) Total number of evacuees: 100



(b) Total number of evacuees: 850



(c) Total number of evacuees: 1600

Fig. 3. CDF of evacuation time.

B. Simulation results

Fig. 3 shows the results for scenarios i)-iii) when the total number of evacuees is varied. The solid curves present cases in which evacuees who have obtained the information on the recommended route or the closed road segment take aggressive behavior, and the dotted curves present cases in which they do not take aggressive behavior.

1) Reduction of evacuation time by sharing evacuation support information: The results shown in Fig. 3 (b) and (c) indicate that as the number of evacuees increases, the effectiveness of providing recommended evacuation routes increases. Comparing scenarios (ii) and (iii) in Fig. 3 (c), we can see that providing recommended evacuation routes reduces the evacuation completion time for all evacuees by about 12%. In scenarios (i) and (ii), all evacuees try to evacuate along the shortest route, avoiding the closed road segment. Thus, many evacuees concentrate on some road segments. In the simulation map used in this study, evacuees concentrated on roads #2, #3, and #6. In scenario (iii), it is confirmed that the provision of recommended evacuation routes would lead some evacuees to routes with roads #13, #14, and #17, thus easing the concentration of evacuees on certain evacuation routes.

On the other hand, the result shown in Fig. 3 (a) shows that when the total number of evacuees is 100, the evacuation time tends to be shorter in scenario (ii), in which only information on the closed road segment is shared, than in scenario (iii). When the density of evacuees on the road is low, even though the congestion on the shortest route is not high enough to cause traffic congestion, the evacuees may be led to an uncrowded but long route, which may result in a longer evacuation time.

2) Impact of aggressive evacuation behavior on evacuation time: The results shown in Fig. 3 show that the evacuation time is shortened by introducing the aggressive behavior of evacuees in all simulation scenarios. It is because the evacuee tries to go in the direction along his/her evacuation route, even if it is against the flow of other evacuees. The degree of effect of providing recommended evacuation routes based

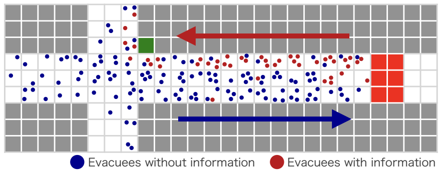


Fig. 4. Formation of two-way lanes

on congestion differs from whether evacuees act aggressively or not. When evacuees take aggressive behavior, and the total number of evacuees is 850, the difference in the time for all evacuees to complete evacuation in scenarios (ii) and (iii) is 18 time steps. This value corresponds to about a 10% reduction in the time to complete evacuation by providing the recommended evacuation route. On the other hand, when evacuees do not take aggressive behavior, the effect of providing the recommended evacuation route (i.e., the difference between scenario (ii) and (iii)) is about a 17% reduction in the time to complete evacuation. Thus, providing the recommended evacuation routes is more effective when evacuees do not take aggressive behavior. The reason for this can be explained as follows. When evacuees do not take aggressive action, more evacuees will stop at their current position due to congestion because they do not go against surrounding evacuees, while evacuees can move if they are aggressive even in a congested condition and their evacuation time can be short. Thus, the evacuees who are not aggressive can more effectively avoid congestion by following recommended routes, and the time to complete evacuation becomes short.

Fig. 4 shows a snapshot of the simulation animation of scenario (i) when evacuees take aggressive behavior when obtaining information about closed road segments or a recommended route (evacuation assistant information). By seeing the animation, we can see that evacuees who have obtained evacuation assistant information take aggressive evacuation behavior against the flow of evacuees who have not obtained the information and continuously rush to the closed road segment form two lanes, one aiming the closed road segment and one leaving the closed road segment. On the other hand, when evacuees do not take aggressive behavior even when they obtain evacuation assistant information, such two lanes are not observed. This result means that evacuees' aggressive behavior leads to making multiple lanes. As a result, in most scenarios where evacuees act aggressively, they can evacuate within 22 minutes (i.e., the maximum tsunami arrival time) even if the number of evacuees increases, while evacuation complete time when evacuees are not aggressive is longer than 22 minutes.

VI. Conclusions

To support rapid evacuation in natural disasters, we proposed a method to distribute information on recommended evacuation routes selected based on estimated congestion as well as the location of closed road segments via heterogeneous (short-range broadband and long-range narrowband) wireless DTN and confirmed its effectiveness through simulations. The method works even if existing wireless communication infrastructure, such as cellular networks, is unavailable. Also, since the method uses short-range broadband and long-range narrowband wireless communications, the method works even if the density of evacuees is low, and it is hard to deliver information via only short-range communication between evacuees. We also designed a cellular automaton-based simulation model to treat the aggressive behavior of evacuees who have obtained evacuation assistant information and incorporated it into the simulations.

We confirmed the performance of the proposed method, focusing on the effect of providing recommended evacuation routes selected according to congestion estimated from the information collected via the DTN and the effect of the aggressive behavior of evacuees. From the simulation results, we confirmed that providing recommended evacuation routes effectively reduces the time to complete evacuation, especially when the density of evacuees is high. Also, we observed that the aggressive evacuees' behavior contributes to forming two-way evacuation lanes and smoothing their mobility.

In this paper, we assumed that only one fixed relay node provides a recommended evacuation route based on the degree of congestion, and evacuees do not forward the recommended evacuation route, even though they forward information on closed road segments. In reality, multiple fixed relay nodes can provide recommended evacuation routes, and evacuees can forward information about recommended evacuation routes. We plan to extend the simulation model to incorporate these cases. Also, the validity of the proposed model of evacuee's aggressive behavior needs to be confirmed. It remains for our future work.

Acknowledgment

This work is partly supported by KAKENHI 22H03579 and JST CREST JPMJCR21D2.

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