On Interactions between Evacuation Behavior and Information Dissemination via Heterogeneous DTN

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Recommended Paper

On Interactions between Evacuation Behavior and Information Dissemination via Heterogeneous DTN

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Abstract: Disaster information-sharing among emergency personnel and residents helps facilitate quick and safe evacuation from disaster areas. However, it is difficult to communicate with people in disaster areas when communications infrastructure is not available. To tackle this problem, we have been developing a heterogeneous delay/disruption tolerant network (DTN)-based disaster information-sharing system that uses long-range narrowband links (e.g., LoRa) and short-range broadband links (e.g., Wi-Fi). Our disaster information-sharing system disseminates evacuation recommendations, evacuation routes, and other vital information to residents in disaster-stricken areas by the store-carry-forward method using residents' mobile devices and relay nodes installed at roadsides, fire departments, and shelters. Since evacuee movements and information dissemination in heterogeneous DTN affect each other, and since understanding those interactions will facilitate the development of more efficient disaster information distribution strategies, we developed a simple cellular-automaton-based simulation model to investigate data dissemination in our heterogeneous-DTN system and analyzed those interactions. Our simulation results revealed a particular complication that we have named the "leaving-behind phenomenon," in which people who have obtained information on damaged roads take detours to a shelter before providing the same information to the evacuees that will approach the damaged road. Based on our simulation results, we report on a way to alleviate this problem by installing fixed relay nodes at the most suitable locations.

Keywords: disaster, evacuation behavior, Delay/Disruption Tolerant Network (DTN), disaster information network system

1. Introduction

"Maps are essential. Planning a journey without a map is like building a house without drawings." —Mark Jenkins— [1] Evacuating in response to disasters without accurate information is like walking in a strange area without a map. The aftermath of the Great East Japan Earthquake of March 11, 2011, showed that swift evacuations away from secondary disasters such as tsunamis are essential to save lives, and that achieving quick evacuations requires ensuring people can reach shelter as fast as possible. However, victims can be forced to take detours during evacuations when the planned routes to shelters become unavailable due to damaged roads, bridges, etc., which means that people who have not been informed about those detours can become caught up in secondary disasters and lose their lives. Therefore, it is vital to disseminate information on damaged roads and alternative shelter routes to everyone concerned as rapidly as possible.

In the aftermath of the Great East Japan Earthquake, Japanese car manufacturers began providing updated automobile route maps showing passable roads [2], [3]. These maps, which were created based on Global Positioning System (GPS) trace data collected by automobile telematics services, helped rescue teams and volunteers reach earthquake victims and made it easier to carry relief supplies into the damaged areas. Unfortunately, these passable automobile route maps took a few days to create after the earthquake, and numerous lives that were lost to the tsunamis might have been saved if it had been possible to compile and disseminate them immediately after the earthquake.

When disasters strike, communications infrastructures in the affected areas are likely to suffer damage, and portions of those systems may become unavailable. In the case of the Great East Japan Earthquake and the tsunamis that followed, severe damage to communication infrastructure prevented communications between emergency personnel and area residents for several days during a period when approximately 8.5 million homes suffered power outages [4]. These outages affected 1.9 million telephones connected to fixed-line networks, which accounted for more than 50% of the total number of telephone lines in the affected area,

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and 29,000 mobile phone base stations [5]. Thus, the Japanese earthquake early warning system, which is built on a public broadcasting system and cellular networks, may not function adequately in the event of a major earthquake [6].

Some disaster information-sharing systems that are independent of communication infrastructures have been proposed in previous studies [7], [8], [9]. NerveNet [7] built wireless mesh networks consisting of multiple fixed base stations such as Wi-Fi access points. Relay-by-Smartphone [8] provides a delay/disruption tolerant network (DTN) built on Bluetooth-based device-to-device communications among the evacuees' mobile devices. However, these existing infrastructure-independent disaster-information sharing systems often cannot function effectively during disasters because they depend on a single communication medium and do not have an alternative means of communication if that medium is unavailable.

In response to the problem described above, we have been developing a heterogeneous-DTN-based disaster-information sharing system [10], which uses short-range broadband links (e.g., Wi-Fi, Bluetooth) and long-range narrowband links (e.g., LoRa and Digital Convenience Radio (DCR) [11]). This system facilitates the sharing of disaster-related information (e.g., the location and state of damaged roads and buildings, evacuation instructions, and rescue requests) among evacuees, disaster-response headquarters/personnel, and evacuation shelters. Because the system uses both long-range narrowband and short-range broadband wireless links, it overcomes the weak point of each wireless type. In other words, the short communication ranges of Wi-Fi and Bluetooth are supplemented by LoRa, and Wi-Fi supplements the low LoRa data rate. Therefore, using the wireless functions of our DTN, information can be shared more reliably among evacuees and emergency response personnel/facilities during disasters, even in isolated areas that are outside the coverage of normal two-way radio signal communications.

Evacuee behavior and evacuation-route information dissemination in a heterogeneous DTN will affect each other. For example, when evacuation route information is disseminated, the density of evacuees on the affected roads will change, and that density change will affect the connectivity among evacuee handheld and fixed relay nodes. These connectivity changes mean that updated evacuation-route information may not be delivered to some evacuees, while it will reach other evacuees who might not have received it and change their behavior.

This paper investigates interactions between evacuee behavior and data dissemination in a heterogeneous DTN by using a cellular automaton-based simulation model, and discusses a fixed relay node placement strategy that facilitates the rapid movement of evacuees to shelters. The simulation results showed that some evacuees might not receive evacuation information and may fail to take the most suitable evacuation route even if such information has been disseminated via a short-range wireless link-based DTN. This occurs because evacuees who have received the evacuation information will respond by moving to the shelter quickly before they have opportunities to forward the information to more distant evacuees. To alleviate this condition, we investigated fixed relay node layouts with short- and long-range wireless communication functions and found that installing fixed relay nodes at intersections near damaged roads can help facilitate quick evacuations.

The remainder of this paper is structured as follows. Section 2 describes existing disaster information-sharing systems that operate independently of cellular and optical fiber networks, and related work on the effects of disaster information-sharing on evacuee behavior. Section 3 describes the basic design of our heterogeneous-DTN-based disaster information-sharing system, while Section 4 presents the simulation model used to investigate interactions between disaster information dissemination and evacuee behavior. Section 5 shows the simulation results and the effectiveness of information dissemination during an evacuation, while we discuss a fixed relay node placement strategy based on those simulation results that can facilitate rapid evacuations in Section 6. Finally, in Section 7, we conclude this paper and discuss our future work.

2. Related Work

This section provides an overview of existing disaster information-sharing systems and reviews studies that analyzed evacuee behavior. Following the Great East Japan Earthquake, the Japanese Cabinet Office issued a report stating that numerous victims had encountered difficulties due to insufficient information on road congestion and damage [12], [13], primarily because media types that depend on communication infrastructures, such as cellular networks and radio, were unavailable due to electrical blackouts and communications traffic congestion. In response to this problem, several disaster information-sharing systems that do not rely on cellular communications infrastructure have been proposed as ways to facilitate evacuations [7], [8], [14], [15], [16].

2.1 Disaster Information-sharing System

Inoue et al. propose a regional wireless access platform called NerveNet [7] that can be used to share information through a wireless mesh network using multiple fixed base stations. The mesh topology of NerveNet makes it tolerant to link disconnections and fixed base station failures that may occur in the aftermath of a disaster, because the transmitted data can circumvent damaged fixed base stations. Meanwhile, Álvarrez et al. propose a novel emergency network concept that uses Bluetooth Mesh, which is a large-scale multi-hop sensor network composed of Internet of Things (IoT) devices in smart homes and smart offices, to share disaster information when the cellular communication infrastructure fails [14]. Their system, which is also based on a mesh topology, provides resilience because there is no single point of failure. It also enables residents to communicate with each other when the cellular communication infrastructure is unavailable.

Nishiyama et al. propose a system called Relay-by-Smartphone [8] that enables people to communicate via multi-hop, device-to-device, store-carry-forward transmissions. In this movement-based method, when a device containing relay information encounters another mobile device, it transmits the relay data, after which the receiving device does the same when encountering new devices. Separately, Fujiwara and Miwa proposed a DTN-based disaster evacuation guidance scheme constructed from mobile evacuee nodes that rely on evacuee cooperation [15]. In this system, when an evacuee encounters a damaged road segment during an evacuation, he or she records the information on his/her mobile device. After that, when he/she encounters other evacuees, the information is shared through direct communication between mobile devices via Bluetooth or Wi-Fi Direct. Thus, the evacuees can proceed along routes that avoid the damaged roads discovered by other evacuees. However, this scheme requires evacuees to input the location of damaged roads into the application manually.

In contrast, Komatsu et al. propose an evacuation guidance scheme that reduces the evacuee device operations required to collect information on damaged roads [16]. This scheme uses a DTN installed on the evacuees' mobile devices to exchange information on damaged roads via Bluetooth or Wi-Fi. Instead of manual inputs, the scheme estimates damaged road segments from differences between presented evacuation routes from a calculation based on existing maps and the traces of evacuees. The scheme then recalculates routes based on the newly discovered information and presents the updated routes to evacuees.

Next, Asia-Pacific Telecommunity (APT), which is an intergovernmental organization that operates in conjunction with telecom service providers in Asia, established specifications for vehicle-based disaster information and communication system called V-HUB [17]. The V-HUB system assumes that people will share disaster information, such as shelter locations and victim status reports, using automobile-based communications media when public networks fail during and after large-scale disasters. V-HUB collects disaster information through mobile device terminals carried by vehicles and individuals and builds a network through multi-hop connections between vehicles. The vehicles use the store-carry-forward topology when no other vehicles are within communications range.

However, all of the above methods use only short-range wireless communication to exchange information. In those methods, since the communication range of links is just a few tens of meters, isolated evacuees who have no other evacuees in their vicinity cannot obtain information updates via those schemes. If a disaster information sharing system uses both short- and long-range communications, it is possible to share information more extensively and robustly.

2.2 Effect of Information Dissemination on Evacuation Behavior

As mentioned above, when evacuees obtain updated disaster information, they may change their evacuation behavior based on that information. For example, they may change their route after receiving updates directing them in different directions from the route they were initially following, and those evacuation route changes may affect road congestion, which may successively affect the progress of subsequent evacuees. Because of this, several studies have analyzed the effects of information dissemination on evacuation behavior [16], [18], [19], [20].

In one such study, Komatsu et al. propose a scheme that estimates damaged roads and shares the resulting information using DTN through direct communications between evacuee mobile devices and communication infrastructure such as cellular networks [16]. They also evaluated the effectiveness of their proposed evacuation guidance scheme using the Opportunistic Network Environment (ONE) [21] simulator. The simulation results showed that information sharing reduces evacuation times and that the system's effectiveness improves as the number of participating evacuees increases. Although the damaged road information is helpful for evacuees who are heading toward the damaged road segment, the evacuees who already have that information will proceed towards the shelter. Hence, Komatsu et al. pointed out that information propagation in the direction opposite to the evacuation direction is a significant factor, and that the effective use of communication infrastructures is one way to achieve it. However, they did not mention how many fixed base stations were needed to support evacuations.

In another study, Okaya and Takahashi simulated evacuee movements when staff members verbally guided people away from a building [18]. To accomplish this, they modeled and simulated verbal information communications among people in a building and found that the use of an evacuation guide changed evacuee behavior and shortened evacuation times. However, the simulation also showed that the evacuation guidance caused new congestion in the building passageways that delayed the evacuation of some people. Here, we should note that Okaya and Takahashi only simulated verbal information sharing in their building evacuation scenarios and did not consider wireless communications and wide area evacuations, such as in an area struck by a major earthquake.

Meanwhile, Aschenbruck et al. proposed a mobility model that realistically represents human movements based on an analysis of civil protection tactical issues [19]. More specifically, they modeled the movement of people among different areas such as incident sites, casualties treatment areas, and hospital zones. They then compared their model with the random waypoint model and showed their model was capable of specific node distributions that result in heterogeneous node densities and more significant relative mobility levels. Furthermore, they found that average link breakage times were lower for networks with more comprehensive communication ranges.

Uddin et al. proposed a map-based mobility model for DTN systems in post-disaster situations in which the mobility of both rescue workers and victims is considered [20] by extending the ONE simulator to include post-disaster population movements. In this model, the victims move towards shelters, and the rescue workers move towards the victims to supply food relief. When comparing their model with the random waypoint model in ONE, the authors found that network behavior depends significantly on the mobility model. They assumed the communication nodes to be only available for rescue workers and volunteers. They also did not consider situations in which all victims held communication devices.

3. Heterogeneous DTN-based Disaster Information Sharing System

This section describes a heterogeneous-DTN-based disaster

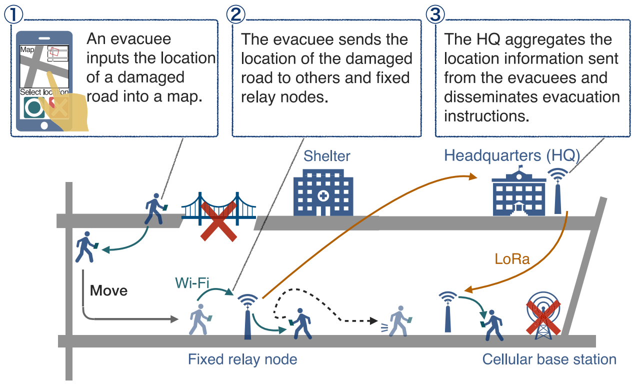

Fig. 1 Overview of heterogeneous DTN-based disaster information sharing system.

information-sharing system and explains issues related to the interaction of evacuee behavior and information dissemination in such systems.

3.1 Overview

This section discusses our proposed heterogeneous-DTN-based disaster information-sharing system, an overview of which is shown in **Fig. 1**. We begin by assuming that evacuees will use smartphones to send/receive evacuation route information to/from wireless stations via short-range broadband links. We also assume that fixed relay nodes that have been placed at disaster headquarters, fire stations, shelters, roadsides, etc., have both short-range broadband links and long-range narrowband links. For example, fixed relay nodes can be installed in vending machines, which have batteries and provide Wi-Fi access point services in disasters [22]. Fixed relay nodes can also be installed in streetlights, traffic lights, etc. The layout of wireless relay stations should be carefully determined to save the devices' cost and maintenance cost without losing their effect on assisting evacuation. The mobile devices and fixed relay nodes share information, such as the locations of damaged roads and shelters, the disaster scales of roads and buildings, evacuation instructions, and rescue calls from damaged areas via a heterogeneous DTN constructed with short-range broadband links (e.g., Wi-Fi and Bluetooth) and long-range narrowband links (e.g., LoRa and DCR). Cellular links can also be used in our disaster-information sharing system if they are available.

The combined nature of this system covers the specific weak points of each wireless communication type by spreading information over multiple wireless communication types. For example, when people only use Wi-Fi, and there are few available communication nodes around them, they cannot easily send information to destinations several kilometers away since there are too few communication nodes that support multi-hops. In such situations, LoRa and DCR, which have communication ranges exceeding 1 km, can expand the area where information can be distributed. However, LoRa and DCR data rates are low, and few people carry devices that can use those links. Therefore, communication devices that have LoRa and DCR installed are typically widely scattered fixed relay nodes. In contrast, when the distance between communication nodes is short, the communication nodes transfer information via Wi-Fi and Bluetooth to compensate for the low LoRa and DCR data rates, which means they can provide secure communications in remote and infrastructure-isolated areas using their long-range narrowband links.

Our system uses store-carry-forward data transmission, which is a technology for carrying and transporting information across communication-isolated areas in which communication nodes do not always have end-to-end links. The DTN system improves connectivity between isolated areas when transmitting data from disaster headquarters to villages or evacuees in radio blind areas/spots or areas where the communications infrastructure/equipment has been damaged. Since emergency vehicles provide nodes that carry disaster information between disaster headquarters and isolated areas, this helps ensure that people in those areas can maintain emergency communications in post-disaster environments.

When an evacuee discovers a damaged/impassable road and inputs its location to a mobile device, the mobile device sends the location information to neighboring mobile devices and fixed relay nodes via short-range broadband wireless links, after which the evacuee proceeds to the shelter with the information retained in his/her device. The fixed relay nodes send the location information received from the evacuee's mobile device to other fixed relay nodes, available mobile devices, and the disaster headquarters via both short- and long-range wireless links. The fixed relay nodes aggregate similar information, such as information related to the same location, to reduce network traffic. The disaster headquarters then disseminates updated evacuation instructions, including the damaged road segment locations and necessary shelter detours to evacuee mobile devices via heterogeneous wireless links. This process ensures that evacuees who receive the information can take the most suitable route to the shelter. In addition, to maximize the number of people receiving the updated evacuation instructions, the fixed relay nodes and evacuees that have received the disaster headquarters updates send those instructions to other evacuees in their vicinity.

3.2 Evacuation Behavior and Data Dissemination Interaction Issues in a DTN

Evacuation behavior and data dissemination in a DTN interact because damaged road location information will lead to evacuation instruction changes, and these changed instructions cause evacuees to change their routes. Evacuees may also change their evacuation routes based on damaged road location information from nearby evacuees before receiving updated evacuation instructions from disaster headquarters. Since evacuee movements change the distances between their devices, these changes can affect the connectivity between the devices and their ability to carry and forward disaster information in the DTN. This also affects subsequent data dissemination. Therefore, investigating issues related to interactions between evacuee movements and disaster information dissemination when using a heterogeneous DTN is essential for improving the system's disaster information distribution strategies. Furthermore, analyzing evacuee movements when people share disaster information will be helpful for making quick and safe evacuation plans in response to tsunamis and floods.

4. Evacuation and Communication Models

This section describes a simplified cellular automaton model that we implemented to investigate interactions between evacuee behavior and information dissemination via a heterogeneous DTN.

4.1 Model Overview

Ideally, to accurately investigate interactions between evacuee behavior and data dissemination in a DTN, a simulation model should be designed to handle the effects of the various components, including the acquisition of damaged road locations, the degree of damage, evacuee mobility levels, radio propagation levels, data delivery protocols, available communication media, road capacity, and other related factors. However, since modeling the details of all these components would complicate the model excessively and make the system's general behavior more difficult to understand, we designed a simple cellular automaton model to simulate evacuee behavior and communications.

In this model, roads and intersections are modeled as a set of aligned cells, and road lengths are defined based on the number of cells on each road segment. The maximum cell capacity, defined as the maximum number of evacuee nodes in each cell, can be configured. The road capacity, which is the maximum number of evacuee nodes on a road segment, is the sum of each cell capacity. Evacuee nodes determine their current position based on a unique number assigned to each cell, referred to hereafter as the cell ID. When reaching a damaged cell, the evacuee records the damaged cell ID and sends it to nearby nodes using a short-range broadband link.

4.2 Evacuation Model

Each evacuee is modeled as a mobile node that moves between cells while proceeding toward the shelter at each time step. All evacuees start evacuation when the simulation time is 0 sec, which means that all evacuees notice the disaster at the timing and start to move immediately. The end of evacuation of an evacuee is defined as the time when the evacuee reaches the shelter. The simulation ends at the time when all the evacuees have reached the shelter, and the time is defined as *all evacuation completion time*. We assume all evacuee nodes have a map of the simulation area and the ID of the shelter cell. Each evacuee node can recognize its current location and damaged cells by their cell IDs. **Figure 2** shows an overview of the evacuation model. At each time step, each evacuee performs the actions listed below:

(i) Looks for the evacuation route. When each evacuee node starts to evacuate or when the evacuee knows the location of a damaged cell, the evacuee node looks for the shortest route from its current position to the shelter cell. The evacuee nodes that have been informed about damaged cell IDs search for the shortest route that allows them to avoid the road segment that includes the damaged cell.

(ii) Moves to the next cell. The evacuee then moves to the next cell along the shortest route. When the next cell is full, the evacuee remains in the current cell. When the next cell is a damaged cell, the evacuee records its cell ID.

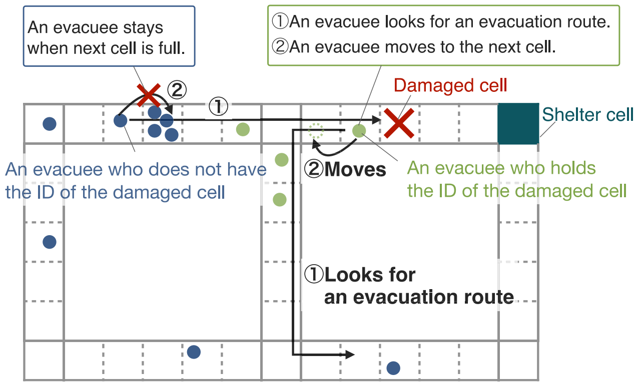

Fig. 2 Cellular automaton evacuation behavior model.

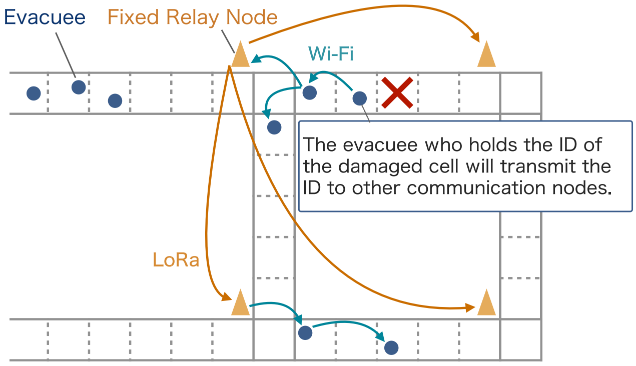

Fig. 3 Cellular automaton communication model ($R_{\mathrm{wlan}} = 2$, $R_{\mathrm{lora}} = 20$).

(iii) Sends the damaged cell ID to other evacuees and fixed relay nodes. The details of this process are explained in the next subsection.

4.3 Communication Model

Figure 3 shows an overview of our communication model in which both the evacuee and fixed relay nodes use a short-range broadband link, but only the fixed relay nodes use a long-range narrowband link. This model assumes that Wi-Fi is used for the short-range broadband link, and LoRa is used for the long-range narrowband link. The evacuee and fixed relay nodes that have received the ID of the damaged cell send that data to all neighboring communication nodes. The communication nodes that receive the cell ID then send the information to their neighboring nodes in the same time step, thus repeating the process and more thoroughly disseminating the ID of the damaged cell. In our model, the ID can be delivered to all evacuees that can be reached in the simulation map within a time step (= two seconds), in which a pedestrian can move for two meters. We assume that the map size is limited, the packet size is sufficiently small, and some smart flooding scheme that can avoid the broadcast storm problem in ad hoc networks (e.g., Refs. [23], [24]) is used. Thus, a message for delivering the ID of a damaged cell to all evacuees that can be reached in multi-hop data delivery can finish in a time step.

Each evacuee and fixed relay node can communicate with other communication nodes within a R_{wlan} radius from itself via Wi-Fi. R_{wlan} indicates the Wi-Fi range. Each fixed relay node can also communicate with other fixed relay nodes within a radius of R_{lora} from itself via LoRa. Here, R_{lora} indicates the LoRa range, and $R_{\mathrm{lora}} \gg R_{\mathrm{wlan}}$. Each fixed relay node transmits the damaged cell

ID using LoRa only once. When an evacuee node receives a damaged cell ID, it updates its evacuation route and broadcasts the cell ID in the next time step. When a fixed relay node receives the ID of a damaged cell, the fixed relay node broadcasts the cell ID using both LoRa and Wi-Fi in the next time step. None of the nodes will send any content that has been sent in any same time step.

To simplify matters, this model does not consider packet losses and radio attenuation. However, since the message size is less than 100 bytes and the number of messages exchanged in one simulation time step is less than 300, short-range broadband link traffic is sufficiently smaller than the 2.4 GHz-band Wi-Fi minimum bitrates of 1 Mbps. Therefore, the effect of those issues on our simplified communication model is expected to be minor.

5. Simulation

This section reports on simulations of the heterogeneous DTN-based disaster information sharing system conducted using the simplified cellular automaton-based model to investigate interactions between evacuee behavior and information.

5.1 Simulation Configuration

We used a map of a 1.2 km × 0.8 km area consisting of 17 road segments and 12 intersections, as shown in **Fig. 4**. In these simulation maps, only one of the cells is configured as an impassibly damaged point on a road segment. This damaged cell was set in the middle of a road segment. The shelter is placed at one of the intersections. **Table 1** shows the simulation parameters. This simulation model does not consider packet reception errors or delays caused by wireless channel congestion because the traffic generated in the simulation scenario is sufficiently low. Assuming that the size of a damaged road message is 100 bytes, all cells are full, and all evacuees broadcast the message in a time step of 2 seconds, the maximum received data size that one evacuee receives in a time step B_{wlan} is derived as follows:

$$B_{\text{wlan}} = (25\,\text{cells} \times 4\,\text{direction}) \times 4\,\text{evacuees/cell} \times 100\,\text{bytes} = 40 \times 10^3\,\text{bytes} \quad (1)$$

The maximum data size for one fixed relay node via the long-range narrowband link in a time step depends on the number of fixed relay nodes within LoRa communication range R_{lora}. In the scenario, $R_{\text{lora}} = 8$. Thus, the maximum data size received by one fixed relay node in a single time step via a long-range narrowband link is 8 × 100 bytes = 800 bytes, which means that the transmission rate for the long-range narrowband link has to be larger than 3.2 kbps to receive 800 bytes.

We used the following three data-sharing models for comparison in our simulations:

(a) **DTN**: All evacuees share the damaged cell ID via the heterogeneous DTN. When evacuees obtain the ID of the damaged cell, they detour away from the damaged cell before they reach it.

(b) **No sharing**: Evacuees do not share information. Each evacuee detours around the damaged road segment after encountering it.

(c) **Oracle**: All evacuees know the damaged cell location from the beginning of the scenario and move on the shortest route from their initial position to the shelter while avoiding the damaged cell.

In the DTN scenario, fixed relay nodes are placed at all intersections. However, since real-world disasters can damage fixed relay nodes, we conducted simulations covering cases in which each fixed relay node was damaged. The working state of the relay node did not change during the simulations.

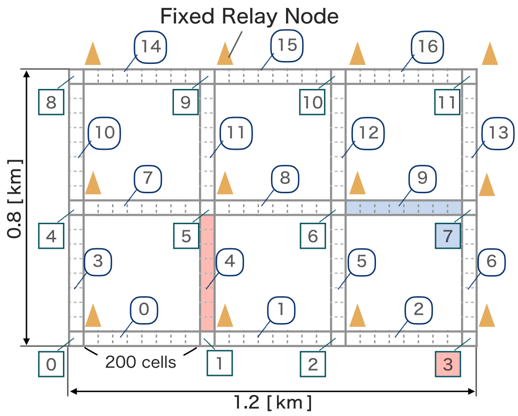

Fig. 4 Simulation scenario.

Table 1 Simulation parameters.

Parameters	Values
Cell scale	2.0 m × 2.0 m
Maximum number of evacuees per cell	Four people
Evacuee movement speed	1.0 m/sec.
Number of evacuees in simulation area	300 people
Evacuee initial position	Assigned randomly
Seconds per time step	2.0 sec.
Wi-Fi communication range R_{wlan}	50 m (25 cells)
LoRa communication range R_{lora}	1,000 m (500 cells)
Simulation time	80 min. (2,400 timesteps)

5.2 Evacuation Times

In this section, we evaluate the distribution of *evacuee arrival times*. An *evacuee arrival time* is defined as the time when an evacuee arrives at the shelter. In the DTN scenario, we simulated cases in which some or all of the fixed relay nodes were damaged. **Figure 5** shows a cumulative distribution function (CDF) graph of the evacuee arrival times when the number of active fixed relay nodes is N, the damaged cell is the middle cell of road segment #9, and the shelter cell is intersection #7. Note that each curve in the graph includes cases in which different relay nodes are damaged. For example, the $N = 2$ case includes various cases where any two fixed relay nodes are working, and the others are damaged, such as a situation in which only intersections #1 and #2 are working, or in which only intersections #4 and #6 are working, etc. We ran 1,000 simulations with different random seeds for each scenario.

As shown in Fig. 5 where the number of evacuees who can evacuate quickly increases as the number of active fixed relay nodes rises, all the evacuee arrival times are shorter in the DTN case than in the no-sharing case. However, in some cases, a number of evacuees arrived at the shelter late because they had not received a message containing the damaged cell ID. This situation occurs when the early arrivers leave the damaged road

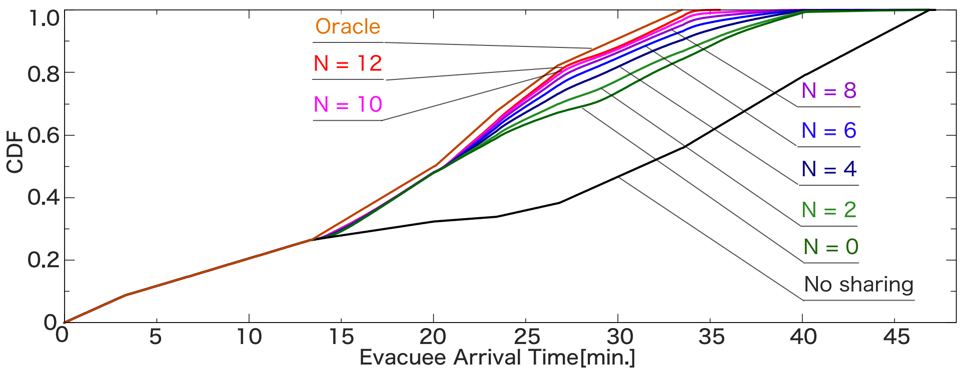

Fig. 5 Distribution of evacuation times for each evacuee (Shelter #7. Damaged road #9).

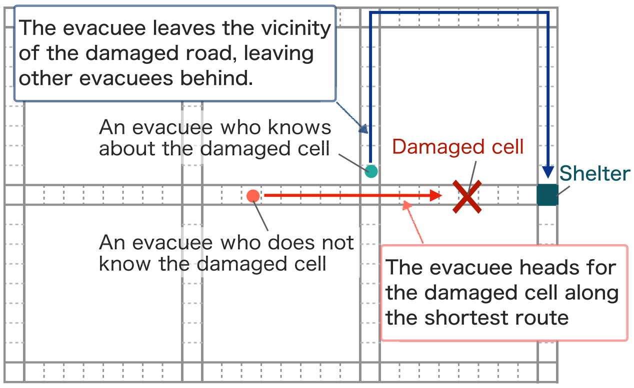

Fig. 6 Leaving behind phenomenon.

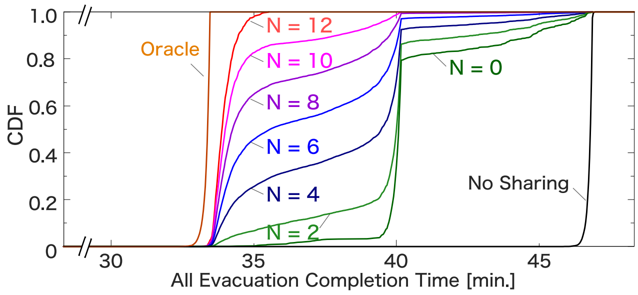

Fig. 7 All evacuation completion times (Shelter #7. Damaged road #9).

segment and proceed to the shelter before latecomers approach close enough to receive updated information on the damaged road segment (**Fig. 6**). We refer to this as the "leaving behind phenomenon" and determined that it can occur in the vicinity of damaged road segments without active fixed relay nodes. In such situations, evacuees who are too far away from evacuees holding ID information on the damaged cell cannot obtain that information from them and continue heading toward the damaged road segment. However, if they can obtain the ID of the damaged cell from a fixed relay node, they can take an alternative route and bypass the damaged road segment.

5.3 Evacuation Time for All Evacuees

Next, we focus on the time when all evacuees arrived at the shelter. We evaluate *all evacuation completion time*, which is defined as the time when all evacuees have arrived at the shelter. That is, *all evacuation completion time* is the time point when the last evacuee enters the shelter cell. **Figures 7** and **8** show CDFs

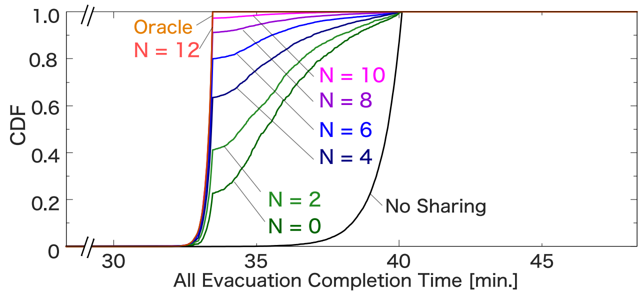

Fig. 8 All evacuation completion times (Shelter #3. Damaged road #4).

of all evacuation completion times obtained with various random seeds. Figure 7 shows the results for a scenario in which the shelter is at intersection #7, and the damaged road segment is at the middle cell of road #9, while Fig. 8 shows the results for a scenario in which the shelter is at intersection #3, and the damaged road segment is set at the middle cell of road #4.

In these figures, it can be seen that when the DTN is used, the all evacuation completion time can be reduced using a sufficient number of working fixed relay nodes because evacuees can take other routes and bypass the damaged cell based on the damaged cell ID information provided by the fixed relay nodes. In the DTN cases shown in Fig. 7, when the number of working fixed relay nodes is eight or more, the all evacuation completion times for all cases are within 40 min regardless of which fixed relay nodes are damaged. In addition, as the number of active fixed relay nodes increases, the number of evacuees who arrive at a shelter early increases as well. In the case shown in Fig. 8, the all evacuation completion time is less variable than that shown in Fig. 7, thus indicating that the effectiveness of installing fixed relay nodes depends on the locations of the damaged road segment and the shelter.

6. Effective Locations for Fixed Relay Nodes

We investigated the optimal locations for one or two fixed relay nodes using the same map shown in Fig. 4. We found that installing fixed relay nodes at all intersections is the most effective way to reduce all evacuation completion times. However, in the real world, the number of fixed relay nodes that can be installed is limited due to budget constraints and location conditions. Therefore, to make it easier for evacuees to arrive at shelters quickly, it is crucial to identify the optimum locations for emplacing fixed relay nodes. Accordingly, we simulated cases when only one or

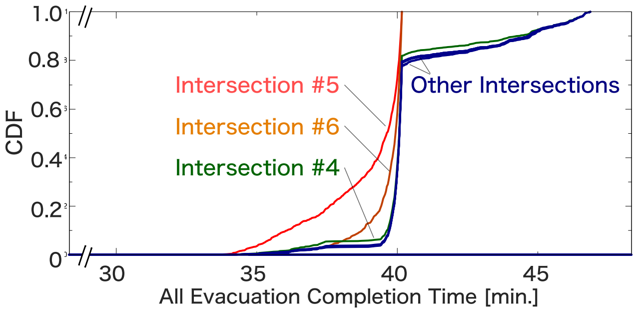

Fig. 9 All evacuation completion times when one fixed relay node is placed (Shelter #7. Damaged road #9).

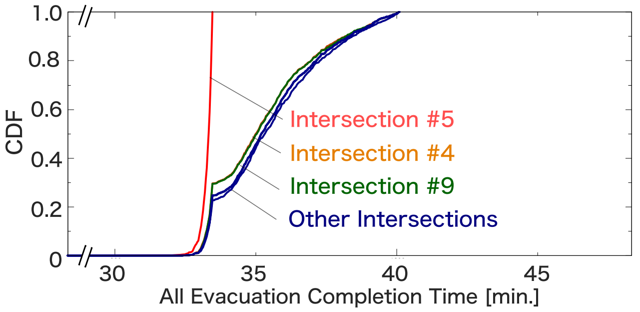

Fig. 10 All evacuation completion times when one fixed relay node is placed (Shelter #3. Damaged road #4).

two fixed relay nodes are placed on the map.

6.1 Optimum Location for One Fixed Relay Node

Figure 9 shows the CDF for all evacuation completion times when only one fixed relay node is placed, the shelter site is located at intersection #7, and road segment #9 is damaged. Each curve represents the cumulative distribution of all evacuation completion times by intersections. When a fixed relay node is placed at intersection #5, the all evacuation completion time is shorter than in any other case. The all evacuation completion time when a fixed relay node is at intersection #6 is the second-least short in the simulation results. **Figure 10** shows the CDF for all evacuation completion times when only one fixed relay node is placed, the shelter site is located at intersection #3, and road segment #4 is damaged. The red curve shows the best time, which represents a case when a fixed relay node is placed at intersection #5.

In these simulated scenarios, intersections #5 and #6 are the optimal locations for shortening evacuation times when only one fixed relay node is placed, because they are nearest to the damaged and congested road segments many evacuees will traverse if they are not aware of the damaged cell. Therefore, these fixed relay nodes have a high potential for disseminating information about the damaged road.

6.2 Optimum Locations for Installing Two Fixed Relay Nodes

Figure 11 shows the CDF for all evacuation completion times when two fixed relay nodes are installed, the shelter site is located at intersection #7, and road segment #9 is damaged. The red curve represents that all evacuation completion time is shortest when the fixed relay nodes are placed at intersections #4 and

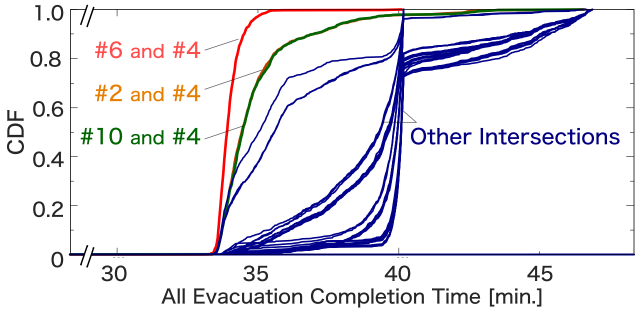

Fig. 11 All evacuation completion times when two fixed relay nodes are placed (Shelter #7. Damaged road #9).

#6. The runners-up are the orange and green curves. The orange curve corresponds to a case when the fixed relay nodes are placed at intersections #2 and #4, while the green curve corresponds to a case when the fixed relay nodes are placed at intersections #4 and #10.

Since intersections #2, #6, and #10 are near the damaged road segment, the fixed relay nodes at those intersections can obtain and disseminate information on the damaged road segment quickly. And, the fixed relay node at intersection #4 can quickly obtain information from the fixed relay node nearest the damaged road segment and then send that information to evacuees who are far away from the damaged road segment. Additionally, since the congested road segments are located near intersection #4, which many evacuees will traverse if they are unaware of the damaged cell, the fixed relay node at intersection #4 can quickly send information to numerous evacuees soon after disasters.

6.3 Discussion

From these results, the features of the optimum locations for fixed relay nodes can be summarized as follows:

- Near the damaged road segment
- Near congested road segments that will be traversed by numerous evacuees.

As explained above, the fixed relay nodes near the damaged road can quickly obtain information about road damage from evacuees after disasters and then provide that information to both nearby evacuees and other fixed relay nodes. However, since it is generally unknown which road segments will be damaged before a disaster, we can place the fixed relay nodes at the road segments that are most likely to be damaged during disasters and those that will significantly impact evacuation times. Since fixed relay nodes near the congested road can send information to numerous evacuees, congested road segments are good candidate locations for fixed relay node placements.

7. Conclusions

This study investigated interactions between evacuee behavior and information dissemination via a heterogeneous DTN using a simple cellular automaton-based simulation model. From the results of simulations, we found that even if a DTN is used, evacuees may fail to receive information because of the "leaving behind phenomena", which means some evacuation times will remain excessive. We also found that fixed relay nodes can shorten evacuation times and that the optimum locations for fixed relay node placements are near damaged and congested road segments.

In our future research, we intend to develop more detailed simulation models. The road layout used in the simulations in this paper was arranged in grid road topology. Thus, the effect of the detour was not serious. In general, road topology is not balanced, and the effect of the detour will be more serious. In addition, the difference in the density of evacuees will affect the message delivery and the fastest evacuation route. It is important to consider different evacuee characteristics, such as reaction to received information, moving speed. Correctness of information (e.g., old information, misunderstanding, and malicious false information) will also affect the evacuee's behaviors. We will investigate the effect of a non-uniform initial distribution of evacuees' positions, which is generally affected by the road topology and the object's layout. We plan to use real maps, an accurate wireless communication model, and evacuation behavior models based on realistic building/shelter arrangements, the population in areas, and reliability of the information. Through more detailed simulations, we plan to clarify the fixed relay node installation appropriate to shorten evacuation time.

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Editor's Recommendation

This paper proposed the heterogeneous wireless communication systems for delivering disaster information considering to information type, data size, destination, and priority. The author have clarified the required quality of wireless link and designed an estimation method to satisfy them. This effort will not only contribute to information delivering in disaster area, but will also be an achievement that can be effectively used in general system design of heterogeneous communication systems. thus this paper is selected as a recommended paper.

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