Cooperative Evacuation Guidance Methods in Large-Scale Disaster Situations Based on Wi-Fi Sensing Data

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Abstract: This study introduces a Wi-Fi packet sensor developed to acquire headcount distribution data, which are obtained by deploying several of these sensors in a large-scale event, as well as describes the results of evaluating the proposed distributed and coordinated evacuation guidance method in a disaster using multi-agent simulation. The results confirm that by balancing the guide loads, it is possible to evacuate all evacuees from the venue in a shorter time than before the addition of the load balance. Furthermore, it was confirmed that if the evacuation route indicated by the guide did not significantly change the congestion situation, it was important for evacuees to choose another exit route at their discretion.

1 INTRODUCTION

In recent years, crisis management measures have become increasingly necessary because of the intensification of natural disasters and the spread of epidemics. Additionally, it is necessary to actively promote business improvement and development to overcome the economic slump caused by global unrest and other factors.

We aim to address these problems by identifying the number of visitors and human flow in real time in large commercial facilities and large-scale event venues where a large number of people gather to efficiently guide evacuations in the event of a disaster, prevent infectious diseases by avoiding congestion, and promote economic activity to optimize store layouts in regular times (Yamada et al., 2022; Asano et al., 2024; Watanabe et al., 2024).

In this paper, a Wi-Fi packet sensor developed for low-cost, real-time detection of the number of people is described and a distributed cooperative evacuation guidance method is proposed as its application for a potential disaster in a large-scale event held monthly in Hirakata City, Osaka Prefecture, Japan. The proposed method was implemented using multi-agent simulation technology, and its evaluation the results are discussed.

[a] https://www.oit.ac.jp/english/research/ist/computer/index.html#lab3202

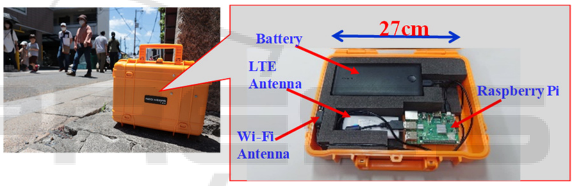

Figure 1: Developed Wi-Fi packet sensor.

2 WI-FI SENSING TECHNOLOGY FOR DETECTING THE NUMBER OF PEOPLE

2.1 Issues and Initiatives

The use of cameras can be a highly accurate method for detecting the number of people in a place; however, it is often avoided because of limitations regarding camera location and blind spots, as well as the fact that the cameras capture the visitor's face. Another method is to use the location information service (e.g., GPS) of a smartphone held by a visitor to analyse human dynamics; however, this method can only be used when a specific application is running, and its accuracy is reduced indoors and underground.

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One method that can address these problems is to estimate the number of people by detecting Wi-Fi radio waves that penetrate materials such as wood and glass and can detect people behind obstacles, thus eliminating the aforementioned problems of blind spots and personal information disclosure. Therefore, it can be used indoors and underground. This Wi-Fi sensing method uses a Wi-Fi packet sensor (hereinafter referred to as "PS") to collect radio waves periodically transmitted from Wi-Fi terminals, such as smartphones, and then extracts and analyses data such as the terminal's MAC address, detection time, and signal strength to estimate the number of people. According to a survey by Japan's Ministry of Internal Affairs and Communications, the smartphone ownership rate as of 2022 was 77.3% (MIC, 2023). However, excluding younger age groups, almost 100% of people own smartphones, and most are considered to have their smartphones and Wi-Fi functions turned on. Therefore, we promote this research and development to consider effectively estimating the number of people using this method (Toyomi et al., 2021; Toyomi et al., 2022).

2.2 Developed Wi-Fi Packet Sensor

Figure 1 shows the Wi-Fi PS. The detected Wi-Fi signals are processed by a Raspberry Pi computer. The Wi-Fi antenna mounted on the device can detect radio waves within a radius of approximately 70 m around the PS. The device is also equipped with a battery that can run for approximately 12 h. A Long-Term Evolution (LTE) antenna and Subscriber Identity Module (SIM) card are also installed, and the detected data can be transmitted to and stored in the cloud so that the detection results can be checked in real time from a remote site. The PS is lightweight and compact, making it highly portable, and the measurements can be started immediately after the power is turned on. Therefore, the PS can be used for last-minute events and for a variety of venues, both large and small, as the number of PSs can be increased according to the size of the venue.

At the main venue of "Hirakata-shuku Kurawanka Goroku-ichi" (commonly called "Goroku-ichi")[1], a large-scale event held monthly in Hirakata City, Osaka Prefecture, Japan, the number of visitors was detected using the developed PS for 2 h, from 11:00 to 13:00, on November 8, 2020 (Sunday). The results confirmed that the PS could detect the number of visitors with reasonable accuracy, with a correlation value of approximately 80% with the manually measured value (true value) (Toyomi et al., 2022). The system is under continuous development and improvement, and it currently exhibits a performance of approximately 90% (Toyomi et al., 2024).

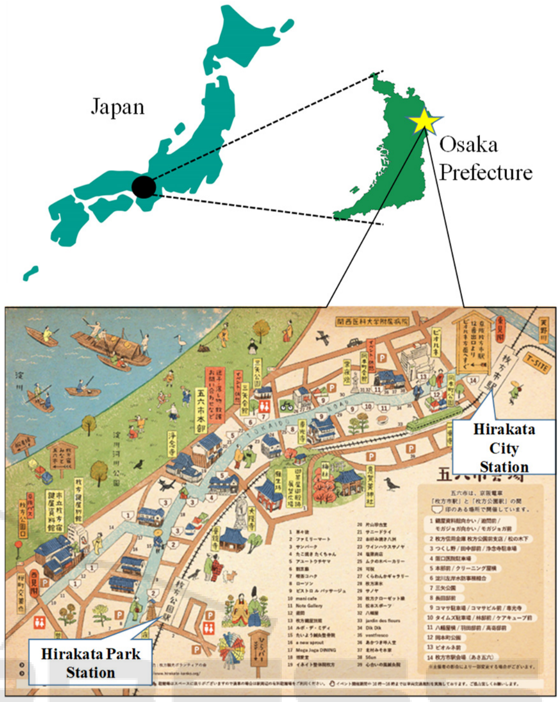

Figure 2: Goroku-ich image map (Japanese version).

3 APPLICATION TO EVACUATION GUIDANCE IN DISASTER SITUATIONS

3.1 Background

Goroku-ichi is a large-scale event held on the second Sunday of every month in Hirakata City, which was once an inn town located on a historical highway that developed during the Edo period (Figure 2). As Goroku-ichi attracts an average of 8,000 people and more than 10,000 people at times, it is necessary to take crisis management measures to deal with natural disasters such as earthquakes, typhoons, and floods, as well as the spread of diseases, such as the coronavirus disease. In response to requests from the Goroku-ichi office, we developed a PS to determine the distribution of people in the Goroku-ichi venue, which is important for crisis management measures, and conducted a variety of field experiments.

[1] https://www.gorokuichi.net/ (Japanese)

Because cars, motorcycles, bicycles, and other vehicles travel in the Goroku-ichi venue, there are four locations where traffic control is required, and approximately ten security guards are deployed to take charge of this task at each location. In this section, we propose a decentralized cooperative evacuation guidance method that assumes the case where multiple security guards cooperate to guide visitors to evacuate in the event of an earthquake in the Goroku-ichi venue, and discuss the results of implementing and evaluating the effectiveness of the proposed method using multi-agent simulation technology. Hereafter, the security guards are referred to as "guides" who guide visitors during the evacuation, and the Goroku-ichi visitors are referred to as "evacuees."

3.2 Proposed Behavior Models for Evacuation Guide

We examined two methods to efficiently guide a large number of evacuees to evacuate the Goroku-ichi venue. In both methods, it was assumed that each guide had his own means of communication and shared information with the others. It was also assumed that the information on the number of evacuees in the venue from multiple PSs was shared.

- **Method 1:** Dynamically determine the zone that each guide is in charge of Goroku-ichi venues are divided into several areas for management. In this method, each guide travels to one of the nearest areas from the current location immediately after a disaster occurs. However, to avoid overlapping the areas they are in charge of, they pass through the areas where there are already guides for the evacuees, go to the area where no one is in charge, and start evacuation guidance for evacuees. However, if the information from the PS indicates that the evacuation route (exit) is more crowded than other routes, the guide informs the evacuees of the route to the next nearest exit. After the evacuation guidance is completed in the assigned area, if there is still an area that has not been evacuated, the guide will go to that area to begin the evacuation guidance.
- **Method 2:** Load equalization added to Method1. This method divides the venue area equally into numbers proportional to the number of guides and assigns these divided areas to the guides. In this case, the divided areas are assigned such that each guide is in charge of an equal number of areas. Immediately after a disaster occurs, the guide first moves to the nearest area in the group of areas that he is in charge of and begins to guide the evacuees. The evacuee guiding method is the same as that used in Method 1. After the guidance of the first area is completed, the guide moves to the area adjacent to the current area in his/her/their area group that has the largest number of evacuees and has not yet been evacuated, and guides the evacuees. When all the guidance in the area group for which he/she/they are in charge of is completed, the guide moves to the area in charge of another guide who has not yet completed the guidance, and guides the evacuation.

3.3 Criteria for Judging Congestion for Determining Evacuation Routes

The proposed methods assume that PSs are placed in appropriate areas and that information on the number of evacuees is shared by each guide to improve the evacuation guidance efficiency. In the evaluation of these methods in Goroku-ichi, we introduced α, which calculates congestion of evacuees from a PS placed at the intersection in a venue exit, where heavy congestion is expected, and uses this as a decision-making tool to select the appropriate evacuation route (see Figure 3). α is expressed as follows:

$$\alpha := n/A \tag{1}$$

where n is the number of evacuees present within the PS measurement range and A is the road area within the measurement range. Specifically, each guide must sum all α on the evacuation route and communicate the route with the smallest total value to the evacuees as an optimal evacuation route.

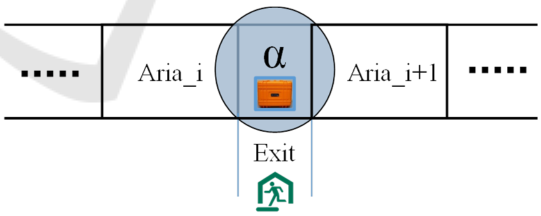

Figure 3: Sensor placement near exits to calculate the congestion degree *α*.

3.4 Evacuee Models

Evacuees remain in place until the guide tells them to evacuate; when the guide provides them with an evacuation route, they start evacuating and go to the venue's exit. If some evacuees started to move in the vicinity, they would look at the surrounding situation, start moving in the direction of most evacuees in progress, and follow other evacuees, even if the route was not communicated to them by the guide.

However, if the guide communicates a different route in this state, the evacuees follow that route. During the process of moving along the route, the evacuator avoids a place by moving to the side if there is a person in the place where he/she/them wants to go. If there are no places to avoid, the evacuee waits for a predetermined period. If the waiting state continues due to congestion, the evacuation route and exits are changed based on the route selection decision criterion β, as follows:

$$\begin{aligned}&\beta: = Tp - Tw - Td,\\&\text{if } \beta > 0, \text{ then: Maintain the current situation;}\\&\text{else: Select another route and exit}\end{aligned} \quad (2)$$

where Tp is the allowable time to maintain the current situation, Tw is the time spent waiting due to the inability to move from the current position, and Td is the time to move from the current position to the current target exit when uncrowded. In other words, only Tp can be changed at the will of the evacuee, indicating that the farther away from the exit, the more likely the evacuee is to change his/her/their intended route to the exit.

We also set the probability γ of selecting another exit when $\beta < 0$. γ indicates the probability (%) of selecting another nearest exit or any other exit, both excluding the current intended exit. For example, if $\gamma = 0\%$, the exit is toward another nearest exit; conversely, if $\gamma = 100\%$, the exit is toward the other exit.

4 EVALUATION

To evaluate the proposed method, we developed a simulator for evacuation guidance after an earthquake in Goroku-ichi and estimated the time required for all evacuees to complete the evacuation from Goroku-ichi venues. As shown in Figure 4, Goroku-ichi is held within 1.1 km from Hirakata City Station to Hirakata Park Station, and is a large-scale event with approximately 200 stores located along a road parallel to the Yodo River on the north side. Goroku-ichi consists of ten management areas (Figure 4: a–j). Additionally, points A–D in the figure are locations where traffic control is required, such as when cars cross venue and where security guards are placed at all times.

4.1 Conditions and Settings

For the evaluation, the number of evacuees and their assignments were based on the total number of visitors (860) measured using the PSs in each of the aforementioned areas on October 13, 2019 (Table 1). Regarding the number of guides, as the labour cost of security guards is an operational issue, two cases were evaluated: one was the same as the current situation, with a total of ten guides (A: 2, B: 3, C: 2, and D: 3), and the other was a total of four guides, one assigned to each of A–D.

Table 1: Initial number of evacuees in each area.

a	b	c	d	e	f	g	h	i	j
45	46	119	145	73	95	64	116	114	43

(Total:860)

Therefore, in Method 1, because the number of areas is ten, if the number of guides is set to four, the assignment of guides to each area is dynamic; however, if the number of guides is ten, there is no dynamic assignment because the number of guides is equal to the number of areas. Meanwhile, for Method 2, the area of the Goroku-shi venue is divided equally into 20 areas, and each guide is assigned to the same number of areas. In other words, if there were four guides, each was in charge of five areas, and if there were ten guides, each was in charge of two areas.

Additionally, it was assumed that the guide would spend a certain amount of time in each area guiding the evacuees and that they would remain in an area for a certain amount of time, which was set at 30 s for this evaluation based on empirical evidence. The communication of the evacuation route by the guide to the evacuees was to be done by voice, and it was assumed that it could be communicated to evacuees within an 18-m radius around the guide's position, this was also based on empirical evidence. Regarding the evacuees' movement after obtaining information on the evacuation route from other evacuees around them, because this movement is propagated, it is assumed that the information can be obtained from people within 1 m of them. If no one was in front

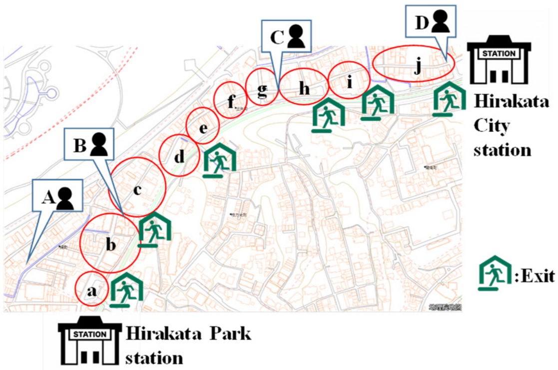

Figure 4: Goroku-ich's ten management areas (a–j), guard locations (A–D), and exits.

of the evacuee, the moving speed of the guide and evacuee was set to 1 m/s, following (Liberto et al., 2020), considering the congestion situation. There were six exits from the venue to the south that the evacuees targeted, and these six exits were also set as destinations for the evacuees in this evaluation (see Figure 4). Furthermore, as the Goroku-shi venue is a single road, when selecting an exit other than the currently intended and next nearest exits, the opposite of the next nearest exit is selected based on γ.

4.2 Results

Table 2 lists the evacuation time simulation results (average of 100 trials) until all evacuees leave the venue, assuming that evacuees do not change the route (exit) communicated to them by the guides. These results are based on a model that reflects the mentality of evacuees who trust the routes communicated to them through guides who know the situation.

Table 2: Evacuation time (s) according to each method when the number of guides is 10 and 4.

	＃Guides＝10	＃Guides＝4
Method 1	716	908
Method 2	639	692

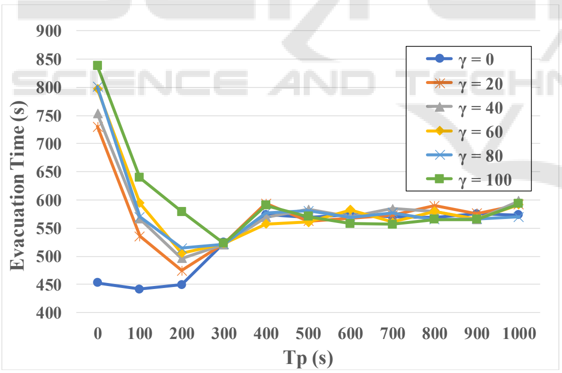

Figure 5: Evacuation time based on γ according to Tp.

Figure 5 also shows the results of changing γ in 20% increments applied to changing to other routes (exits) and then changing Tp from 0 s to1000 s for Method 2, which could evacuate quickly in the case of ten realistic guides. In each case, the average value was obtained from 50 trials. The results show that when γ = 0% and Tp = 100 s, the minimum evacuation time is 441 s; when γ = 100% and Tp = 0 s, the maximum evacuation time is 838 s. When Tp was greater than 400 s, the difference in evacuation time was almost the same, approximately 20 s, for different γ values.

5 DISCUSSION

As can be seen in Table 2, Method 2 with four guides is able to guide the evacuation in a shorter time than Method 1 with ten guides. This is believed to be due to the fact that in Method 2, after completing the evacuation of their own area group, each guide went to help other guides in unguided areas, thus balancing the workload among the guides relatively well. Conversely, in Method 1, there was a large imbalance in the load between guides who were in charge of high-load areas and those who were not.

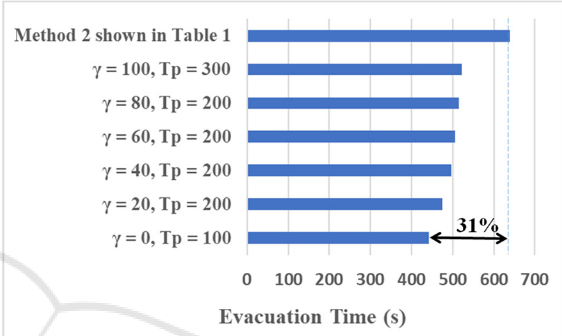

Figure 6: Minimum evacuation time based on γ and Tp.

In Figure 5, for any γ, there is a minimum evacuation time when Tp is less than 300 s. Figure 6 shows the minimum evacuation time and the γ and Tp combination at that time for each of the cases shown in Figure 5. The case with no route (exit) change (Table 1: Method 2 with ten inductors) is also included in this figure for reference. It was confirmed that by changing other routes (exits) according to the situation, the evacuation time could be reduced by approximately 31% (Figure 6). Based on this result, it can be concluded that the most efficient evacuation method is to leave immediately and go to the next-nearest exit if you are stopped by an obstacle during evacuation and the congestion is not resolved after waiting for some time. Although the route information provided by the guide is important, the situation changes from moment to moment. Therefore, it is important for evacuees to make their own decisions.

6 CONCLUSIONS

This paper describes a Wi-Fi packet sensor developed to obtain data on the distribution of the number of people, which is important for crisis management measures against natural disasters and epidemics as well as for improving operations and developing businesses. Using the data measured by this sensor on the distribution of the number of people in a large-scale event, the proposed evacuation guidance method was evaluated using a multi-agent simulation. As a result, it was confirmed that all evacuees could be evacuated from the venue in less than one minute by adding a way to balance the load assigned to each guide. Furthermore, it was confirmed that even if the evacuation route (exit) indicated by the guides did not change the congestion situation, it was important for evacuees to choose another route (exit) at their own discretion. The simulation results showed that it is important to take action based on one's own judgment while referring to information rather than relying on others for one's own life. In this study, the evaluation was based on the distribution of the number of people during daytime hours from 11:00 to 13:00. It is also necessary to evaluate the situation during opening and closing of the event (e.g. when visitors come from Hirakata City and Hirakata Park Stations and when they leave), when the distribution of people is uneven around the two ends of the venue, which will be investigated in future work. Additionally, methods to further shorten the evacuation time must also be investigated.

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