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Information Floating for Sensor Networking to Provide Available Routes in Disaster Situations

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SUMMARY Information floating (IF) permits mobile nodes to transmit information to other nodes by direct wireless communication only in transmittable areas (TAs), thus avoiding unneeded and inefficient information distribution to irrelevant areas, which is a problem with the so-called epidemic communication used in delay tolerant networks. In this paper, we propose applying IF to sensor networking to find and share available routes in disaster situations. In this proposal, IF gathers and shares information without any assistance from gateways, which is normally required for conventional wireless sensor networks. A performance evaluation based on computer simulation results is presented. Furthermore, we demonstrate that the proposed method is effective by highlighting its advantageous properties and directly comparing it with a method based on epidemic communication. Our findings suggest that the proposed method is a promising step toward more effective countermeasures against restricted access in disaster zones.

key words: *information floating, sensor networks, available routes, disaster*

1. Introduction

In cellular mobile communication systems, services are provided through infrastructure elements such as base stations and fixed networks that connect the base stations. However, mobile networks without such an infrastructure have been developed, an example of which is the multi-hop wireless network. In a multi-hop wireless network, a source communicates with a destination through a connected multi-hop wireless path implemented by relay through mobile nodes and by direct wireless communications between these nodes. The mobile ad-hoc network (MANET) is one type of multi-hop wireless network [1].

In multi-hop wireless networks, it is not always possible to construct a connected multi-hop wireless path from a source to the desired destination because relaying nodes are usually distributed randomly. To resolve this problem, a method has been developed to deliver information by direct wireless communication and movement of the nodes that have information. This method uses the spatial distribution of information among mobile nodes and does not require any connected multi-hop wireless paths. We call this method epidemic communication (EP) [2]. EP has been studied widely as a transmission method for delay tolerant networks (DTNs). These studies include network control, design, and performance evaluations that consider the effects of the behaviors of different mobile nodes, such as those on vehicles or pedestrians [2]–[5].

Because EP uses the spatial distribution of information to deliver it to the destination, it is sometimes accompanied by the superfluous flow of information to mobile nodes in unrelated areas. To prevent this problem, various methods have been considered to improve EP. The PROPHET protocol applies the history of previous encounters with other mobile nodes [3]. Another way to avoid this inefficient spreading of information is to permit mobile nodes to transmit information only in designated areas called transmittable areas (TAs). This method is called information floating (IF) [5]–[19]. IF directly prevents the unnecessary spread of information by designating TAs, and thus it is suitable for information delivery to unspecified mobile nodes entering a specific area.

In IF, a source sends information together with the positions of TAs; accordingly, the mobile nodes that receive the information are aware of the TAs' positions. Furthermore, every node is assumed to be capable of detecting its own position by GPS or similar tools. Consequently, the mobile nodes can transmit the information only within the TAs. As a result, IF can deliver information in and around TAs but prevent the spread of information to unrelated areas.

Figure 1 shows an example of how this works. The shaded region is a TA for IF in Fig. 1. Suppose that node A generates message M to be sent in the TA; the black nodes have M but the white nodes do not. Suppose that the wireless communication range of a node is a circle with a radius of r. In this figure, if two nodes are in communication range of each other, we draw a line between these two nodes to indicate that they can directly communicate with each other. The arrow near a node depicts the moving direction of that node.

In Fig. 1(a), nodes A and B are in the communication range of each other; however, A does not send M to B because A is not in the TA. As time passes, A enters the TA and C enters A's communication range; therefore, A sends M to C as shown in Fig. 1(b). In Fig. 1(c), C is in the TA and sends

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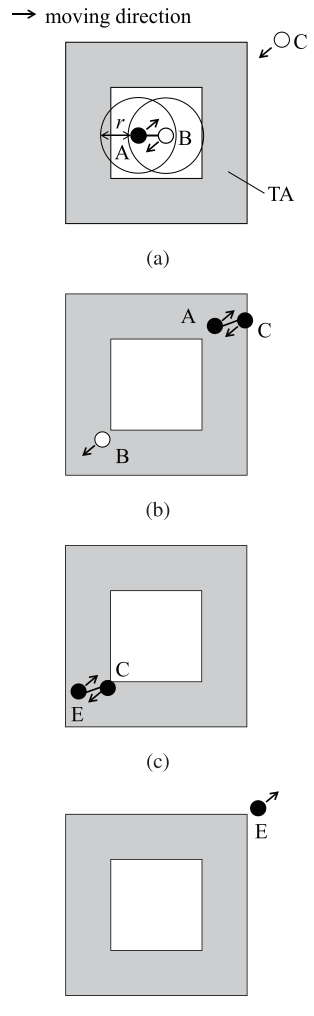


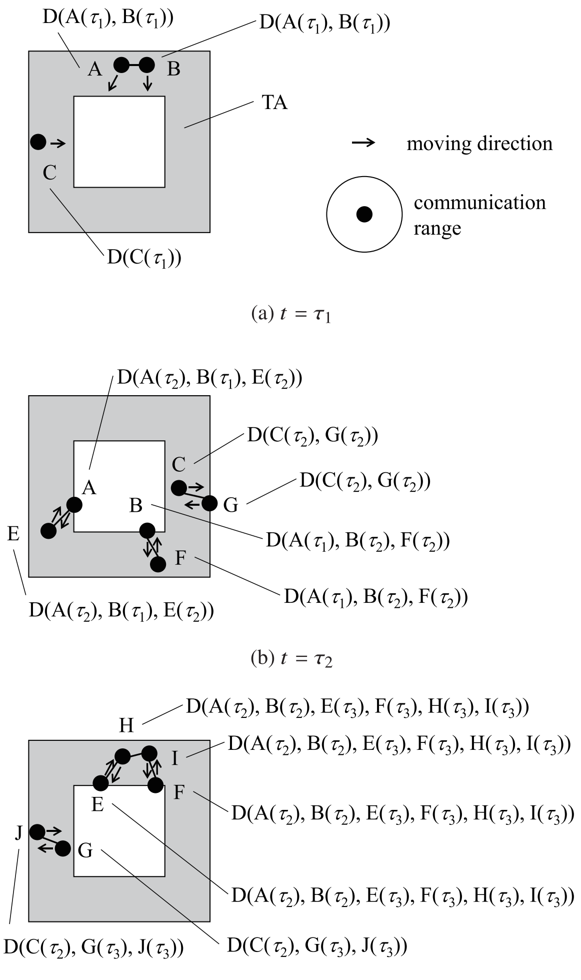
(a)

(b)

(c)

(d)

Fig. 1 Example of IF.



(a) $t = \tau_1$

(b) $t = \tau_2$

(c) $t = \tau_3$

Fig. 2 Example of FST.

M to E. As shown in this example, M, which was originally carried by A, seems to float in the TA and is shared by other nodes that enter the communication ranges of nodes in the TA. This is the basic behavior of IF. When there is no node having M in the TA (Fig. 1(d)), IF will discontinue unless a node with M enters the TA.

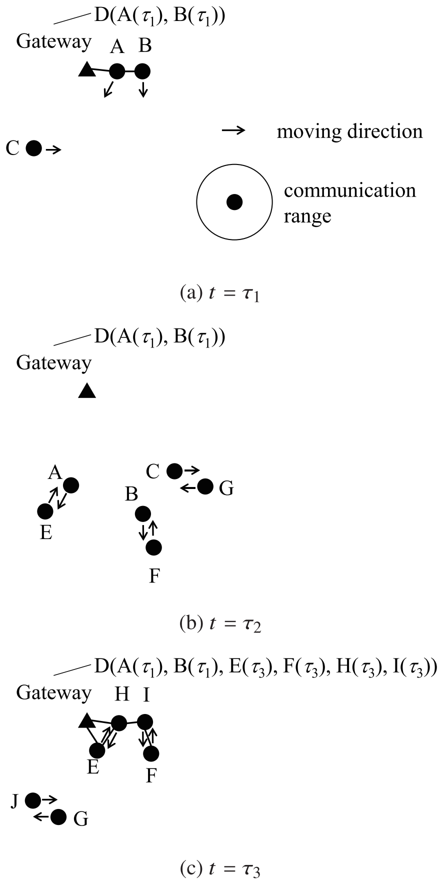
As shown in the example, IF has a lifetime because it ends if all mobile nodes having M leave the TA while no other node with M enters the TA. In implementing IF, the analysis of its lifetime is an important issue [5]–[19].

In this paper, we propose using a new capability of IF used for sensor networking to accumulate information in a specific area without any gateways, which differs from conventional wireless sensor networks (WSNs) [20]. A typical WSN consists of a gateway node and sensor nodes, where data measured by the sensor nodes are carried to the gateway through a wireless multi-hop path achieved by relaying the sensor nodes, which carry out direct wireless communication between them. Namely, the gateway node plays an important role in collecting data in the typical WSN.

On the other hand, if we use IF for sensor networking, we can create a network without any gateway. In IF, mobile nodes (sensor nodes) carry the sensed data to a TA and send the data in the TA to other nodes. Then, the sensed data accumulate in the TA because the carried data are repeatedly sent from nodes in the TA to other nodes entering the TA. In this case, the data are not stored in any specific node or gateway, and IF acts as invisible storage to accumulate data in the actual fields in and around the TA. At the same time, mobile nodes can obtain the stored data by passing through the TA. We call this storing of information by IF "Floating Storage (FST)." Applying this important and interesting capability of IF is a concept that has never been studied to our knowledge.

Here, we explain FST by comparison with a WSN consisting of a gateway and mobile sensor nodes. Figures 2 and 3 illustrate FST and the WSN, respectively. Again, in these figures, if two nodes are in communication range of each other, we draw a line between them. Also as above, we use an arrow near a node to indicate the moving direction.

Consider node α_i. Let $D(\alpha_i(\tau_j))$ be the data sensed by node α_i from the initial time to time $t = \tau_j$. Next, consider mobile nodes $\alpha_{i_1}, \alpha_{i_2}, \ldots, \alpha_{i_n}$. If a node has the set of data



(a) $t = \tau_1$

(b) $t = \tau_2$

(c) $t = \tau_3$

Fig. 3 Example of a WSN.

D($\alpha_{i_1}(\tau_{j_1})$), D($\alpha_{i_2}(\tau_{j_2})$), ... , D($\alpha_{i_n}(\tau_{j_n})$), then we denote this set by D($\alpha_{i_1}(\tau_{j_1})$, $\alpha_{i_2}(\tau_{j_2})$, ... , $\alpha_{i_n}(\tau_{j_n})$). We use this notation to represent the data stored in the gateway or mobile nodes, and we consider the accumulation of these data by FST and the WSN in Figs. 2 and 3, respectively. For simplifying the explanations in these figures, we consider only data exchanges at $t = \tau_1, \tau_2$ and τ_3.

In Fig. 2(a), where $t = \tau_1$, because nodes A and B are in the TA and close enough to directly communicate with each other, they send their sensed data to each other. Just before this direct communication, A has D(A(τ_1)) and B has D(B(τ_1)). Therefore, after the direct communication, A has both D(A(τ_1)) and D(B(τ_1)), namely D(A(τ_1), B(τ_1)), and B also has D(A(τ_1), B(τ_1)). As time passes, A moves to the bottom of the figure. At $t = \tau_2 > \tau_1$ in Fig. 2(b), A has D(A(τ_2), B(τ_1)) and approaches node E, having D(E(τ_2)). Note that the set of data owned by A is updated from D(A(τ_1), B(τ_1)) to D(A(τ_2), B(τ_1)) because A measures new data between τ_1 and τ_2. A and E can directly communicate with each other and are in the TA. Hence, A and E exchange their datasets and, as a result, have the same dataset D(A(τ_2), B(τ_1), E(τ_2)). At $t = \tau_2$, B also approaches node F, having D(F(τ_2)). In the same manner as nodes A and E, B and F exchange the data and have the same dataset D(A(τ_1), B(τ_2), F(τ_2)). At the same time, nodes C and G exchange data and have D(C(τ_2), G(τ_2)).

In Fig. 2(c), where $t = \tau_3$, E and F move to the top of the figure and send D(A(τ_2), B(τ_1), E(τ_3)) and D(A(τ_1), B(τ_2), F(τ_3)) to nodes H with D(H(τ_3)) and I with D(I(τ_3)), respectively. Note that the sets of data of E and F are updated because E and F measure new data between τ_2 and τ_3. Just after direct communication between E and H, H has D(A(τ_2), B(τ_1), E(τ_3), H(τ_3)). In addition, I has D(A(τ_1), B(τ_2), F(τ_3), I(τ_3)) after the data exchange between F and I. At the same time, H and I can exchange their data. Here, H has D(A(τ_2)), and I has D(A(τ_1)), which is older than D(A(τ_2)) and included in D(A(τ_2)). If we receive both old and new data, then we overwrite the old data with the new data. Then, after data exchange between H and I, D(A(τ_1)) disappears and only D(A(τ_2)) is left. Hence, after the data exchange, H and I have the same dataset D(A(τ_2), B(τ_2), E(τ_3), F(τ_3), H(τ_3), I(τ_3)). Also, at $t = \tau_3$, G delivers D(C(τ_2), G(τ_3)) to node J.

As can be seen from this example, the data sensed by mobile nodes accumulate in the mobile nodes in and around the TA and are delivered to mobile nodes in and around the TA. This is the basic concept of FST.

Figure 3 is an example of a WSN with a gateway shown for the same situation of mobile nodes in Fig. 2. In Fig. 3(a), D(A(τ_1)) and D(B(τ_1)) are delivered to the gateway through a multi-hop path. Then, the gateway has D(A(τ_1), B(τ_1)). In Fig. 3(b), there is no node around the gateway. In Fig. 3(c), the gateway receives D(E(τ_3)), D(F(τ_3)), D(H(τ_3)) and D(I(τ_3)) through a multi-hop network. Then the gateway has D(A(τ_1), B(τ_1), E(τ_3), F(τ_3), H(τ_3), I(τ_3)).

These examples show that the FST in Fig. 2 can store D(A(τ_2), B(τ_2), E(τ_3), F(τ_3), H(τ_3), I(τ_3)), although the gateway in Fig. 3 stores the older dataset of D(A(τ_1), B(τ_1), E(τ_3), F(τ_3), H(τ_3), I(τ_3)). Furthermore, FST can store D(C(τ_2), G(τ_3), J(τ_3)), which are not stored in the gateway of WSN in Fig. 3.

As an application of FST, this paper explores it as a way to find and share available routes in disaster situations where the road network is broken and the communication infrastructure, such as cellular systems, is unavailable. In past disasters, probe car systems based on cellular networks [21]–[24] have been used to share available route information for vehicles. In a probe car system using a cellular system, each vehicle measures its position by GPS while moving and sends the measurement results to a data center through the cellular system; however, vehicles obviously cannot share information if they are inside the disaster area but are not covered by the cellular system due to failure of the cellular infrastructure. FST overcomes this problem because it does not need gateways for sensor networking nor the assistance of fixed communication infrastructure. Consequently, FST can deliver information on available routes to mobile nodes as explained below.

Considering the example in Fig. 2 again, suppose that D(A(τ_2)) is the trajectory of node A measured by the node itself. Then, in Fig. 2, the trajectory of A is shared by other nodes using IF. In Fig. 2(c), H receives D(A(τ_2)), included in D(A(τ_2), B(τ_2), E(τ_3), F(τ_3), H(τ_3), I(τ_3)). This means that H can receive the past trajectory of A, namely D(A(τ_2)),

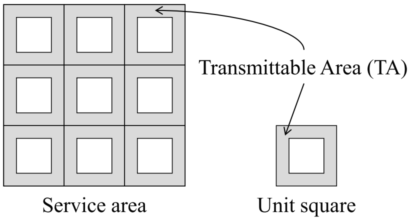


Fig. 4 Service area, unit squares and TAs.

included in D(A(τ_2), B(τ_2), E(τ_3), F(τ_3), H(τ_3), I(τ_3)), in the region toward which H is heading before actually entering that region. Hence, sharing of trajectory data by IF helps mobile nodes choose their routes. Furthermore, mobile nodes other than A also measure their trajectories and send the measured trajectories in the same TA to other nodes. This means that FST accumulates many different trajectories in the mobile nodes in and around the TA.

With these considerations in mind, we propose applying IF to sensor networking based on FST, without using any gateway for sensor networks nor communication infrastructure (i.e., cellular networks), as a way to provide information on available routes during disasters. We propose dividing a service area into squares and setting TAs at the edge of these squares, as illustrated in Fig. 4. We call the square surrounded by a TA a unit square. Consequently, each mobile node can obtain the conditions of routes in a unit square by IF before entering the unit square. We assume the worst-case scenario, where mobile nodes have neither topological information of the road network in the service area nor the ability to download the topological information due to communication infrastructure failure caused by a disaster. Moreover, we propose a way to represent available routes that is suitable for our proposal. We show the results of a performance evaluation by computer simulation and demonstrate the effectiveness of the proposed method by highlighting its advantageous properties and comparing it with an epidemic communication method.

As explained above, FST is considered a new kind of invisible social infrastructure made possible by IF. FST can be used for various purposes, including communications during a disaster, to help people engaged in the reconstruction of disaster areas. Accordingly, FST is expected to help restore sustainable society as a new invisible social infrastructure.

In Sect. 2, we propose an application of IF to sensor networking based on FST and explain FST's ability to provide available routes in disasters. We also provide some background and explain the difference between this proposal and past research. In Sect. 3, we explain our assumptions for the performance evaluation and discuss the finding of this performance evaluation with reference to its computer simulation results. In Sect. 4, we present our conclusions.

2. Proposed Method

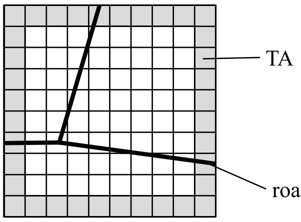
2.1 Outline

As explained in the Introduction, we propose "Floating Storage (FST)," which is a new kind of sensor networking based on IF without any gateway. We use FST to obtain and then provide information on available routes in disaster situations where the communication infrastructure (i.e., cellular networks) is not available, since IF and FST use direct wireless communication between mobile nodes and do not require any communication infrastructure. We assume the worst case, where each mobile node (vehicle) lacks topological information of the road networks and such topological information cannot be downloaded due to failure of the cellular systems.

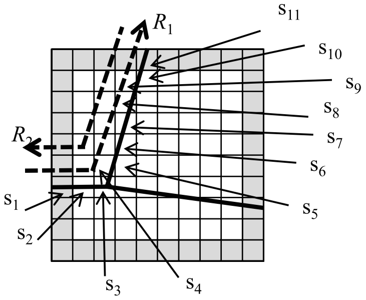
FST is a kind of invisible storage that is made possible by IF. In IF, we define transmittable areas (TAs) and permit mobile nodes to transmit data only in TAs to prevent inefficient spreading of data to irrelevant areas. A mobile node has a direct wireless communication function and a positioning function such as GPS. The mobile node continuously senses its own position to investigate available routes and directly transmits the sensed data to other mobile nodes if it is in the TA. The mobile node can judge whether it is in the TA by the positioning function. For the direct wireless communication, the wireless communication range of a node is a circle with a radius of r. A mobile node that receives data from other nodes transmits these data to other nodes while it remains in the TA. Transmissions made in this way are in turn repeated. As a result, the data sensed by mobile nodes are accumulated in the mobile nodes as explained in the Introduction.

As mentioned, we assume the worst case, where each vehicle lacks topological information of the road networks and such topological information cannot be downloaded. Hence, we have to somehow represent a route without knowledge of the road network in the service area. As an example, consider a unit square of the service area shown in Fig. 5, where the shaded region is a TA and each road is depicted by a bold line. Note that mobile nodes do not have information on the road in advance. We divide this unit square into small squares. A small square is represented by s_i, where $i = 1, 2, \ldots$. We represent the trajectory of a mobile node as a series of these small squares s_i. Consider the two routes R_1 and R_2 in Fig. 5(b). R_1 is represented as a series of small squares s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}. R_2 is the opposite route of R_1 and is thus represented by s_{11}, s_{10}, s_9, s_8, s_7, s_6, s_5, s_4, s_3, s_2, s_1. In Fig. 5(c), we show two more routes R_3 and R_4. R_3 is s_1, s_2, s_3, s_{12}, s_{13}, s_{14}, s_{15}, s_{16}, s_{17}, s_{18}, s_{19}, and R_4 is the opposite route of R_3. A mobile node that moves along R_1 understands that its trajectory R_1 is an available route because of the positioning function, and it can send the information on R_1 as the series of small squares in the TA.

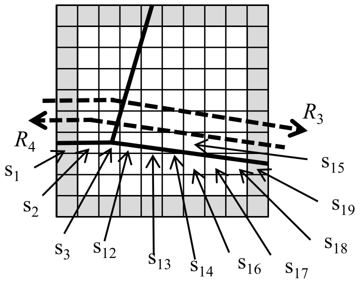
Based on the representation of a route as a sequence of small squares, mobile nodes exchange and store route information by FST. Figure 6 shows an example of this oper-



(a) A unit square, small squares and a TA.



(b) Routes R_1 and R_2.



(c) Routes R_3 and R_4.

Fig. 5 Routes and small squares.

ation. This example is FST in the unit square of Fig. 5. For simplicity, we consider only data exchange at $t = \tau_1, \tau_2, \tau_3$ and τ_4. Suppose that node A moves along R_1 as shown in Figs. 6(a) and (b). In Fig. 6(b), where $t = \tau_2$, A and B are in the TA and in communication range of each other; therefore, they exchange D(A(τ_2)) and D(B(τ_2)). As a result, A and B have D(A(τ_2), B(τ_2)), which includes $\{R_1\}$, namely D(A(τ_2), B(τ_2)) $\supset \{R_1\}$. In Figs. 6(b) and (c), B and C move along R_2 and R_4 from τ_2 to τ_3, respectively. Suppose that, at $t = \tau_3$, B, C, E and F can exchange their data in the same manner. Then, B, C, E and F commonly have D(A(τ_2), B(τ_3), C(τ_3), E(τ_3), F(τ_3)) $\supset \{R_1, R_2, R_4\}$. Consequently, node E can obtain information of R_1 from $\{R_1, R_2, R_4\}$. This means that node E can obtain information of a route before actually entering the route by FST. In Fig. 6(d), we can see another example of data delivery. At $t = \tau_4$, node G can get information on R_4 before entering R_4. As shown in this example, information on available routes is stored in various parts of the TA.

In our proposal, we use a service area consisting of unit squares as represented in Fig. 4. The TA is located at the edge of the unit squares, as depicted in Fig. 4. Mobile nodes entering a unit square always pass through a TA, and thus it is possible to obtain information on available routes. If a mobile node is notified of an available route, the mobile node can follow that route. Otherwise, the mobile node moves ahead along roads without any guidance. The mobile node may stop at a dead end and turn back because it did not know about the dead end in advance. Even without guidance, however, a mobile node may successfully pass through the unit square along an available route. This means that the mobile node finds an available route and can then transmit the route when passing through the TA. Either way, a mobile node must find a route without any guidance in the initial stage because no information has yet been accumulated in and around the TA.

Furthermore, IF does not permit information exchange inside a unit square that is outside of the TA. Accordingly, this feature is expected to reduce the number of exchanges between mobile nodes, which is an advantageous characteristic of IF.

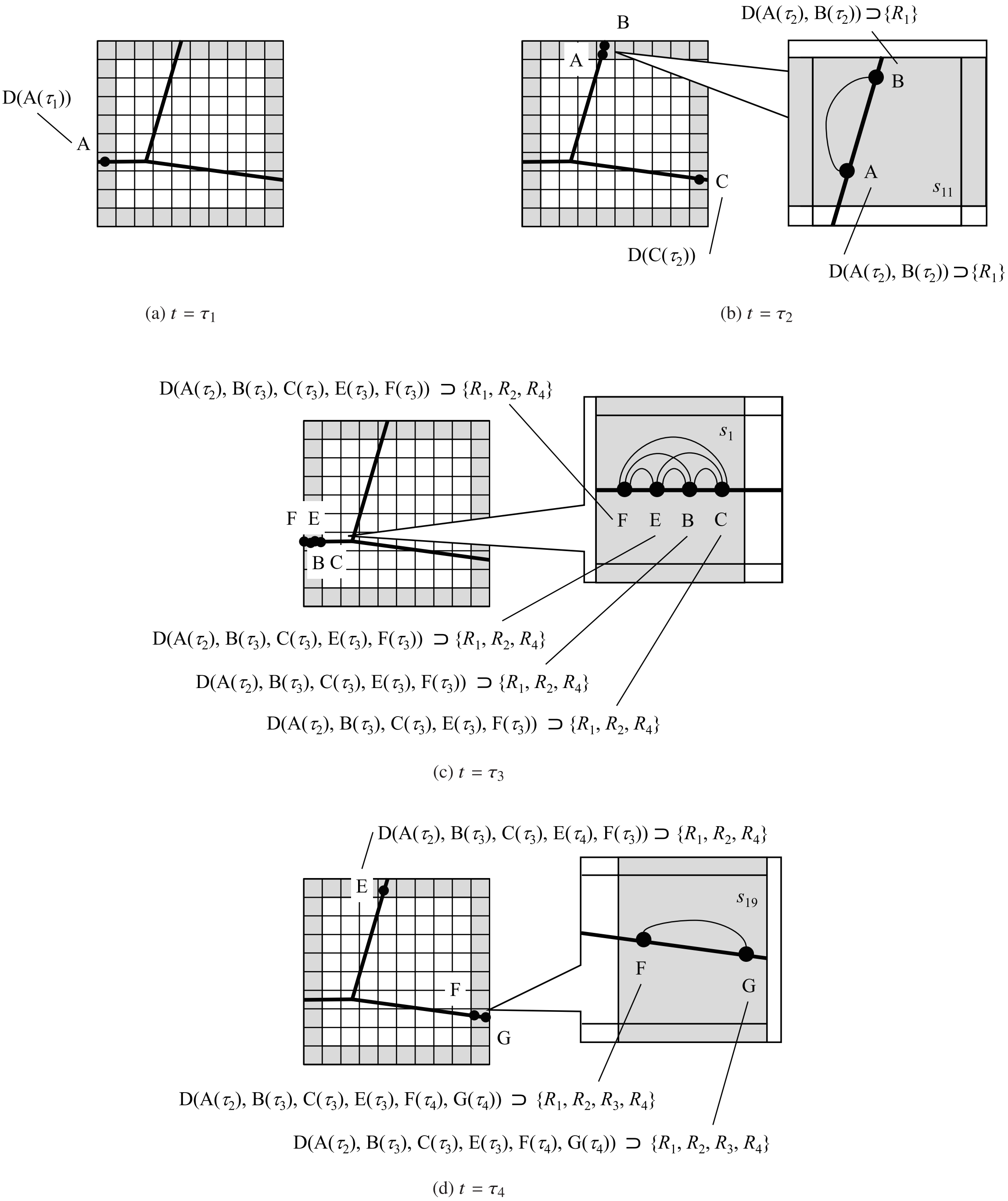
Furthermore, we assume the application software in each vehicle is prepared in advance and that every mobile node uses the same settings made for the service areas, the division of a service area into unit squares, the division of a unit square into small squares, and the TAs. As mentioned, the position and size of the TA are normally sent with the transmitted information; however, in the application presented here, the position and size of the TA are initially given to mobile nodes in advance because the mobile nodes have to cooperate with each other in the initial stage of IF. At the beginning of system usage, each vehicle recognizes the service area, which includes the disaster area, and starts using IF to measure routes and share this information. At the initial moment, vehicles do not have any information; therefore, they move ahead along roads based on the direction of their destination.

This is the basic idea of our method. In the following sections, we explain our method in further detail.

2.2 New Functions of IF to Achieve FST

As mentioned, much of the past research on IF focused on the lifetime of IF, evaluating the mean lifetime, etc. because these studies considered using IF to share just one type of information. On the other hand, in IF for sensor networking to provide FST, mobile nodes store their trajectories while moving and share multiple types of data in and around a TA. Therefore, using the system presented in this paper, mobile nodes transmit different types of data in the TA by designating the same TA even for a variety of data. With this new function, even if some data are lost due to IF stopping for these data, new data measured by other nodes will be carried to the TA and shared among mobile nodes entering the TA. Therefore, we have to consider a new way to evaluate the performance of IF, that is, not only how long IF continues but also how much total data IF stores in the TA.

IF's main role in handling the frequent arrival of new data in the TA is to make the mobile nodes continuously



(a) $t = \tau_1$

(b) $t = \tau_2$

(c) $t = \tau_3$

(d) $t = \tau_4$

Fig. 6 Example of FST that accumulates available routes R_1, R_2, R_3 and R_4.

exchange not only old data but also new data. The data are then virtually accumulated in mobile nodes in and around the TA. However, an environmental situation can change without the arrival of new data in the TA to announce this change. For example, suppose that IF shares the information that route R_j is active and, after time passes, that some of the R_j links become unavailable due to accidents or other reasons. In this case, we should remove the data that indicate that R_j is active from the data stored in the TAs. One approach is to remove all data on the unavailable links in R_j shared in the TA by distributing a message to delete these unavailable links from lists in the TAs. Another is to introduce the lifetime of data because the following will often occur: Even if the data for links of a route disappear from a TA because the lifetime of these data has expired, new data for the same links will again be carried to the TA by other mobile nodes moving along the route if the route is active. In this paper, we introduce the lifetime of data, expecting that fresh data for the same links will be repeatedly carried to TAs.

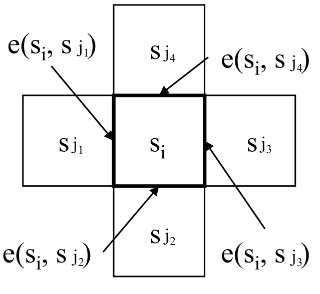
As explained in the previous subsection, IF has an additional property of accumulating multiple types of data. Returning to the example in Fig. 6, the measured data on route R_1 are first carried to the TA at s_{11}; however, the data are useful for mobile nodes entering s_1, and so the data should be carried to the TA at s_1. Furthermore, even if the data stored in the TA at s_{11} are lost because of the end of IF in s_{11}, restoration is possible because the data previously carried from s_{11} to s_1 and stored in the TA at s_1 can be carried to s_{11} again. As seen in these examples, FST makes possible the circulation and restoration of the data.

These IF properties for sensor networking are different from those of an IF system operated individually and have not been studied in past research.

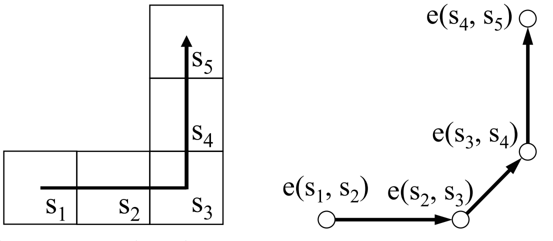
2.3 Representation of a Trajectory in Detail

In this section, we explain how to represent a route with a series of small squares in more detail. Figure 7(a) represents small square s_i surrounded by small squares s_{j_1}, s_{j_2}, s_{j_3} and s_{j_4}. Assume that only one road passes through the side of a small square in this paper. Denote the four sides of s_i by $e(s_i, s_{j_1})$, $e(s_i, s_{j_2})$, $e(s_i, s_{j_3})$ and $e(s_i, s_{j_4})$ as depicted in Fig. 7(a). When a mobile node enters s_i at $e(s_i, s_{j_1})$ and exits at $e(s_i, s_{j_4})$ at time τ_1, the mobile node stores the information as $(e(s_i, s_{j_1}), e(s_i, s_{j_4}), \tau_1)$.

Consider the trajectory of a node in Fig. 7(b). We use a directed graph to represent a series of small squares corresponding to the trajectory. In the directed graph, vertices correspond to the sides of small squares through which the trajectory passes and are designated $e(s_1, s_2)$, $e(s_2, s_3)$, $e(s_3, s_4)$ and $e(s_4, s_5)$. There is a directed link between two vertices if the trajectory successively passes through the two sides corresponding to the two vertices. For example, there is a directed link between $e(s_2, s_3)$ and $e(s_3, s_4)$ because the trajectory passes side $e(s_3, s_4)$ right after $e(s_2, s_3)$.



(a) A small square s_i and its four sides.



(b) A trajectory through s_1, s_2, s_3, s_4 and s_5.

(c) The direct graph representing the trajectory in (b).

Fig. 7 Representation of a trajectory by a directed graph.

Suppose that the mobile node passes $e(s_2, s_3)$, $e(s_3, s_4)$ and $e(s_4, s_5)$ at times τ_1, τ_2 and τ_3, respectively. Then, the mobile node carries the data $(e(s_1, s_2), e(s_2, s_3), \tau_1)$, $(e(s_2, s_3), e(s_3, s_4), \tau_2)$, and $(e(s_3, s_4), e(s_4, s_5), \tau_3)$ and sends them to other nodes in the TA. From these data, mobile nodes obtain information on active links. As mentioned, these data will be removed after their lifetimes expire based on a time stamp. We remove $(e(s_i, s_k), e(s_k, s_\ell), \tau_1)$ after time $\tau_1 + t_e$, where t_e is a constant. If a mobile node receives the same direct links $(e(s_i, s_k), e(s_k, s_\ell), \tau_1)$ and $(e(s_i, s_k), e(s_k, s_\ell), \tau_2)$ measured at different times where $\tau_1 < \tau_2$, then the mobile nodes keep only the new link $(e(s_i, s_k), e(s_k, s_\ell), \tau_2)$ and remove $(e(s_i, s_k), e(s_k, s_\ell), \tau_1)$.

2.4 Route Search and How to Increase Accumulated Data

Available routes represented as directed graphs are accumulated and stored by IF in mobile nodes in and around a TA. By merging the accumulated directed graphs, the mobile nodes can have a larger directed graph. Each mobile node can search an available route in this directed graph using a shortest path algorithm. As the number of directed edges accumulated in the mobile nodes in a TA increases, the directed graph tends to show more candidate routes. Therefore, it is important to maintain sufficient data in a TA.

In the initial stage, no information on available routes is accumulated in the TA. Hence, mobile nodes have to move without any assistance and collect available routes. As time passes, information on available routes is accumulated in the mobile nodes in and around a TA; however, if the nodes follow past available routes, the number of accumulated available routes will not increase. Therefore, mobile nodes should continue to find new routes without following past available routes for a period of time, even if a number of candidate available routes have been accumulated. We denote the length of the time period during which mobile nodes move while neglecting past available routes by t_m.

After t_m has passed, the mobile nodes are no longer in the initial stage and can use information on the past available routes; however, sufficient data may not have been accumulated even after the initial stage. Also, road conditions will change after the initial stage. One example is that some links of the road network will become unavailable due to accidents, construction, or road work. Another example is that a link can become available again after its restoration. The lifetime of the data is defined as explained previously, and this lifetime can eliminate old data. This operation enables us to delete routes that become unavailable in the former example. To find new available routes in the latter example, the mobile nodes must develop new routes even after the initial stage. To do this, some mobile nodes must find routes by themselves. Of course, such nodes are also necessary if the amount of data accumulated in the initial stage is not sufficient.

To find new available routes after the initial stage, we classify mobile nodes into two groups U_1 and U_2. After the initial stage, we make mobile nodes of U_1 find new routes and make those of U_2 follow the past routes provided by FST. A mobile node belongs to U_1 with probability p_m. Although nodes of U_2 do not develop new routes, they update the time stamp of the links based on the received data. We assume that mobile nodes of U_1 correspond to disaster relief volunteers, public service workers, special vehicles such as patrol cars, and so on. In this case, U_2 corresponds to ordinary people, and p_m corresponds to the ratio of the number of people in U_1 to the total number of people in U_1 and U_2. Accordingly, if U_1 is the set of special vehicles for disaster rescue and the size of U_1 is small, then p_m will be small. On the other hand, if we have many disaster relief volunteers and public service workers and U_1 consists of these people, then p_m becomes larger. Thus we evaluate how the value of p_m affects the performance of FST. Based on the above operations, new data will accumulate both in the initial stage and after the initial stage.

2.5 Background: Information Sharing by Probe Car System

A probe car system [21]–[24] enables us to share route information while driving, and it is usually used as a car navigation system. The information is continuously updated by measurements from moving vehicles. In a probe car system using a cellular system, each vehicle measures its position by GPS and sends the measurements to a data center via the cellular system. Because the probe car system stores information on the routes along which vehicles have actually moved, it can grasp active routes and their condition (e.g., the mean velocity). This ability allows a probe car system adopting a cellular system to be used as a map generator providing available routes during disasters in place of a navigation system. In fact, this system was effective during the Great East Japan Earthquake [22]–[24]. However, such information sharing of available routes is not possible in areas where the cellular system fails. Furthermore, the probe car system basically assumes that topological information of road networks is available for use.

Distributed probe car systems have also been considered. Distributed probe car systems do not use a communication infrastructure such as cellular systems but rather share information through direct communication between vehicles. For example, in one study [25], EP was used to share information. In EP, however, information spreads widely to unrelated areas, and the number of information exchanges tends to become large.

Furthermore, the distributed probe car systems also assume that topological road network information is known in advance. Hence, if digital maps cannot be downloaded during a disaster, we need a new method to obtain topological information.

3. Results and Discussions

3.1 Assumptions on Service Areas and Communications

To evaluate the proposed method's basic properties by computer simulation, we begin with our assumptions about service areas. A service area is a square with 12-km sides. There is a road network within this service area. We consider a situation where a disaster causes road failures in a road network with a lattice structure.

As mentioned in the previous section, it is important for the proposed method to collect and accumulate many available routes by FST. To evaluate this capability, we should evaluate the proposed method in a road network with a complicated structure because it is easier to collect many data in a network with a simple structure. Furthermore, the basic concept of the proposed method is that each mobile node measures a route from an origin to a destination and shares the route by FST. Hence, if the origin and destination are disconnected, then a mobile node cannot find any route. Therefore, it is desirable that many nodes have a connected route between the origin and destination. From these viewpoints, a complicated and connected network is desirable for our performance evaluation.

Next, we construct a random network as follows. First, we consider a square lattice where the number of links is n_ℓ and the distance between adjacent intersections is 500 m. Next, we choose and delete n_d links randomly from the n_ℓ links. The deletion corresponds to the road failures as mentioned above. Let r_d be the ratio of n_d to n_ℓ. If r_d is too large, then many links are deleted and the network becomes disconnected. As mentioned, this situation is not desirable for our performance evaluation. Therefore, we choose a value for r_d so that the road network can be nearly connected even after deleting the links. Here, we set r_d to be 0.35, namely $n_d = 420$ and $n_\ell = 1200$, and the road network shown in Fig. 8 is obtained. The network in this figure includes some disconnected links, but almost all links are included in a connected network.

A simulation starts at $t = 0$ and continues in the initial stage until t_m. After $t = t_m$, $1 - p_m$ of the mobile nodes begin to follow information on available routes, while p_m of the mobile nodes keep developing and then finding new available routes, as mentioned.

3.2 Assumptions on IF for Sensor Networking

The size of a unit square is 3 km. Let L_s be the size of a small square to represent a route. Assume that $L_s = 100$ m. Suppose that a TA surrounds the unit squares like the shaded area of Figs. 9(a), (b), and (c) and that the width of a TA is the integer multiple of L_s. The width of a TA is thus denoted by L_w. We assume that each mobile node has a positioning function by GPS or similar tools and can measure its own position correctly. We also assume that a mobile node can communicate with another mobile node if the distance

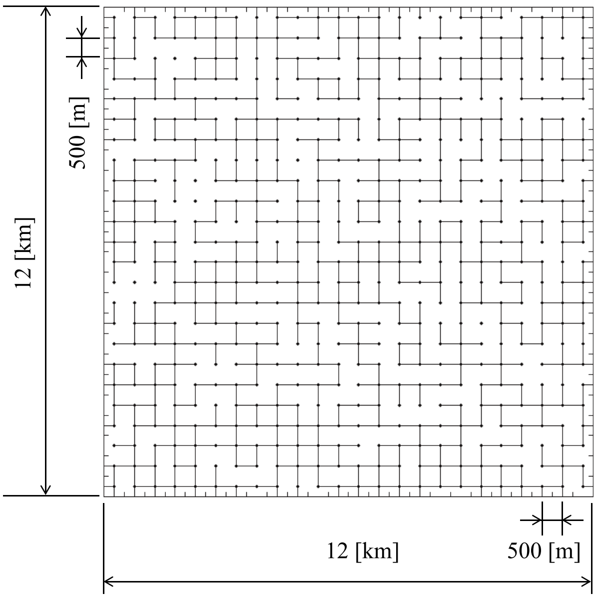
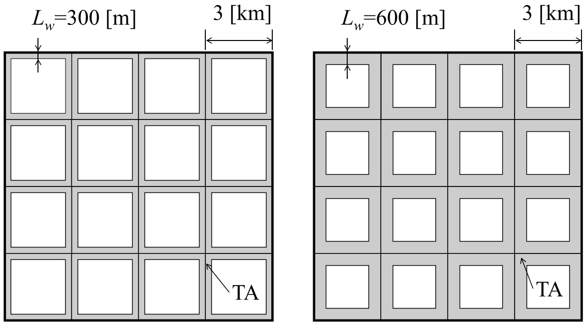
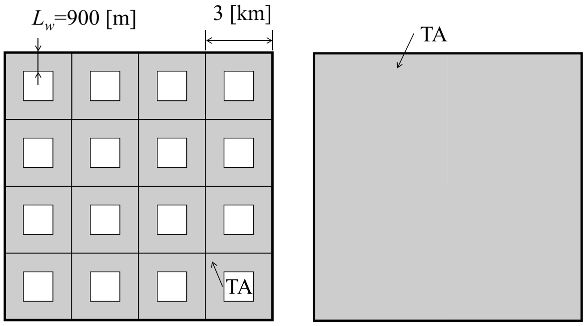


Fig. 8 Road model.



(a) L_w = 300 m

(b) L_w = 600 m



(c) L_w = 900 m

(d) Epidemic Communication

Fig. 9 Arrangements of TA.

between them is less than or equal to a 100-m communication range supposing wireless LAN [10]. We use these simple assumptions for the positioning and communication range because our main interests here lie in how mobile nodes pass each other in a TA to accumulate data to achieve FST and how the data on available routes are accumulated in and around the TA.

The TA in Fig. 9(d) indicates that EP is used because a mobile node can transmit data anywhere.

3.3 Assumptions on Mobility

Assume that a mobile node departs a point on a street in the service area and moves toward a randomly chosen destination point within the service area. Assume that departures from the points in the service area obey a Poisson process at rate λ. Here, $\lambda = 1.5\,s^{-1}$. The mobile nodes are vehicles moving at 36 km/h.

If a mobile node has no available route information, it moves closer to the destination as follows. The node moves along the road until it reaches an intersection. Suppose that the node arrives at an intersection connected to n roads in addition to the road that the node enters. Let θ_i be the angle between the ith road and the direction of the destination. Assume that the mobile node moves along the ith road with probability $\frac{1}{\theta_i} / \sum_{j=1}^{n} \frac{1}{\theta_j}$, where for $\theta_i < 10^{-6}$ we compute $\frac{1}{\theta_i}$ as 10^6 to avoid division by zero. Note that a mobile node tends to move in a direction that brings it closer to the destination. If a mobile node arrives at a dead end, it turns back.

If a mobile node following the route guidance with probability $1 - p_m$ receives information of available routes and at least one path to the destination exists among these received available routes, the mobile node computes the shortest path to the destination and moves toward the destination by following this shortest path. Otherwise, the mobile node tries to move to the destination without any assistance. A mobile node not following any guidance with probability p_m also tries to move toward the destination without any assistance.

3.4 Apparent Advantages in Performance Evaluation

In the performance evaluation, we have to resolve complicated issues regarding the relationship between route guidance performance and node density. In our simulations, as soon as a mobile node successfully arrives at the destination, the mobile node stays at the destination and no longer cooperates with IF. However, if a mobile node cannot receive route information from FST and arrives at the destination after a long detour, the node density in the service area apparently increases and helps IF to continue for a longer time. Hence, in our simulation, to prevent IF's apparent advantage, we prevent the mobile nodes that cannot receive information from FST from cooperating in either IF or route development.

On the other hand, if we prevent the mobile nodes that cannot receive information from FST from cooperating in IF, the number of IF's transmissions decreases. This results in another apparent advantage for IF. Hence, we compare the number of transmissions of IF with that of EP by setting the rate of departure of nodes for EP, with the guidance explained above, to a value smaller than the original value, i.e., to $(1 - p_{fail})(1 - p_m)\lambda$.

3.5 Accumulation Performance of FST

First, we evaluate the accumulation performance of FST by the number of accumulated data in the TA. To ascertain this number, we assume the service area of Fig. 9(a), in which $L_w = 300\,\text{m}$ and $\lambda = 1.5\,s^{-1}$. Here, it is assumed that $t_m = 3600\,\text{s}$ and $t_e = 1800\,\text{s}$. We count the number of directed edges owned by a mobile node passing through the TA. We divide the TA at the edge of the unit square into squares with sides of 300 m. We find the maximum number of directed edges in each of the squares every 100 seconds. This number corresponds to the maximum number of directed edges stored in FST. We show the results at $t = 1200\,\text{s}$ in Fig. 10(a). Figures 10(b) and (c) are the results at $t = 2400\,\text{s}$ and 3600 s, respectively. In these figures, we can see that the data accumulate as time passes and, at $t = 3600\,\text{s}$, the data are accumulated over the entire service area.

We represent the above data in different forms to observe the results in more detail. Figure 11 shows the results for two specific places denoted by TA1 and TA2 in Fig. 10. Figure 11 shows the time transition of the number of accumulated data in TA1 and TA2. The accumulated data gradually increase with time for TA1. On the other hand, for TA2, the accumulated data sometimes disappear or increase rapidly. As mentioned, IF in a local part sometimes discontinues. In this case, the data stored in TA2 disappear. However, the data stored in other parts of the TA can be carried to TA2. This property is unique to FST. These results show that the operation in the initial stage works well.

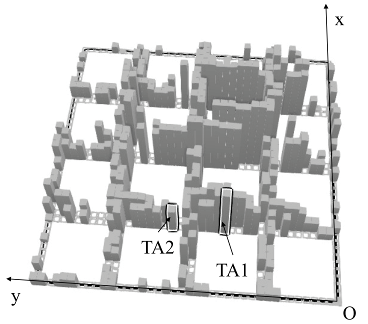
3.6 Success Ratio of Navigation and the Number of Transmissions

Next, we evaluate FST's route guidance performance based on the success ratio of route guidance. The success ratio is defined as the ratio of the number of mobile nodes that successfully arrive at destinations under the route guidance to those that use route guidance. This ratio is computed every 300 seconds to include the mobile nodes originating within the 300 seconds.

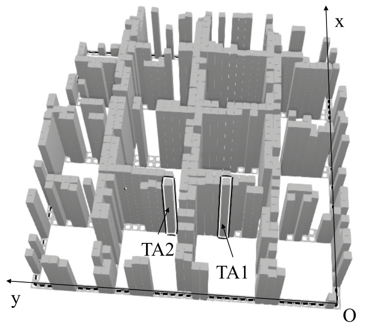
We show success ratios for different values of L_w, t_m and p_m and then compare them. L_w is the width of TA and is considered a factor that affects the lifetime of IF as can be expected from past studies of IF. t_m is the length of an initial stage and is a factor that affects the amount of accumulated data in the initial stage. p_m is also a factor that affects the amount of accumulated data after the initial stage.

Figures 12(a), (b) and (c) show the success ratios for $t_m = 1200\,\text{s}$, 1800 s and 3600 s, respectively, where $p_m = 0.5$ and $t_e = 1800\,\text{s}$. Figures 13(a) and (b) show those for $p_m = 0.2$ and 0.0, respectively, where $t_m = 3600$ s and $t_e = 1800\,\text{s}$. In each of the figures, the success ratio increases as L_w increases because IF improves as L_w becomes larger.

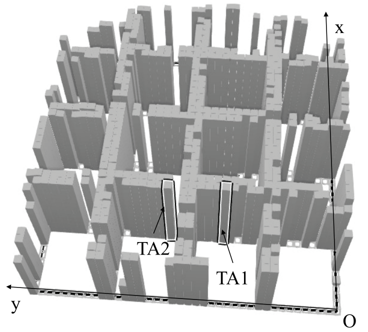
In Fig. 12, we observe the effects of the length of the initial stage t_m on the success ratio. From this figure, for $t_m = 3600\,\text{s}$ and $L_w = 900\,\text{m}$, the success ratio is sufficiently large just after the initial stage, and the success ratio is nearly equivalent to that of EP. Also, for $t_m = 3600\,\text{s}$, the success ratio for $L_w = 300\,\text{m}$, 600 m and 900 m are nearly constant after the end of the initial stage. This means that the length



(a) $t = 1200$ s.



(b) $t = 2400$ s.



(c) $t = 3600$ s.

Fig. 10 Maximum number of directed edges stored in FST.

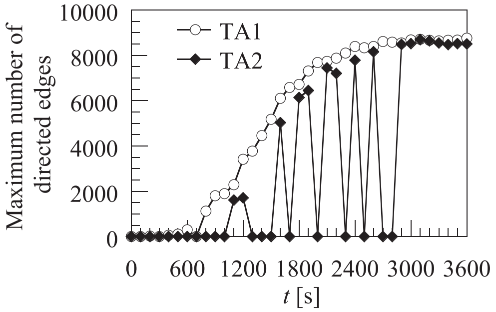
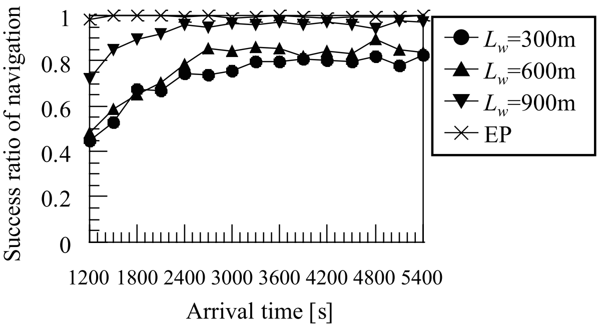
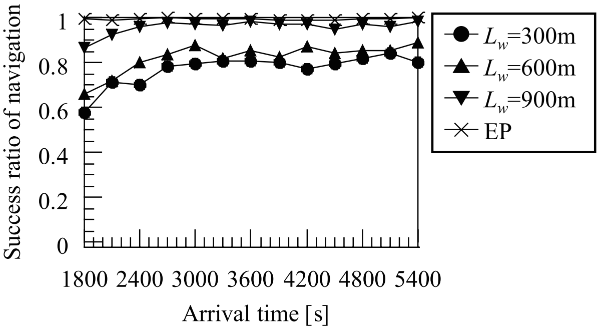


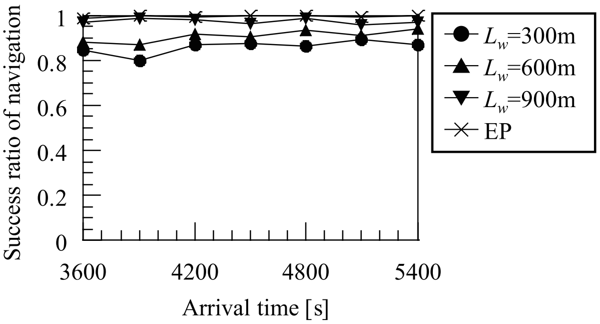
Fig. 11 Maximum number of directed edges stored in FST in TA1 and TA2.



(a) $t_m = 1200$ s.



(b) $t_m = 1800$ s.



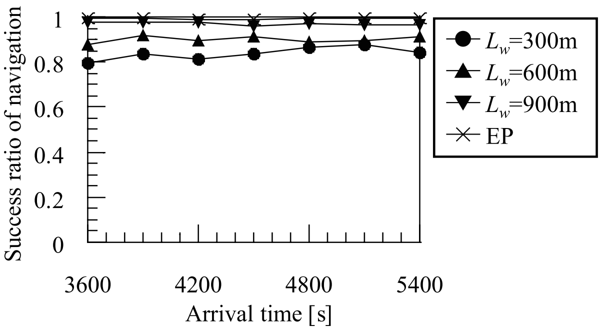
(c) $t_m = 3600$ s.

Fig. 12 Success ratio of navigation, where $p_m = 0.5$ and $t_e = 1800$ s.

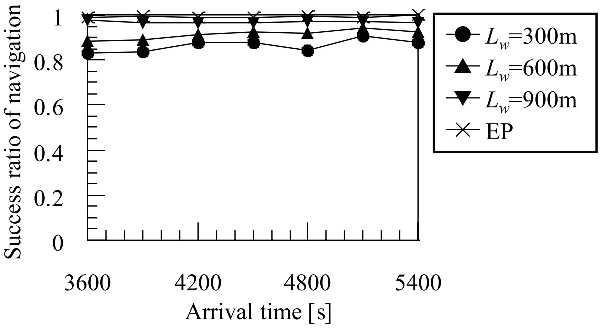
of the initial stage is sufficient for $t_m = 3600$ s. On the other hand, for $t_m = 1200$ s, the amount of accumulated data in the initial stage seems insufficient; therefore, the success ratio is low at the end of the initial stage. As time passes, however, the success ratio increases as the accumulated data increase because the mobile nodes of U_1 keep searching for routes after the initial stage, since $p_m = 0.5 > 0$.

In Fig. 12(c) and Figs. 13(a) and (b), we assume $t_m = 3600$ s. Consequently, the length of the initial stage is considered sufficient as mentioned above. Although these figures show success ratios for different values of p_m, they also show a similar tendency because a sufficient amount of data was obtained in the initial stage.

We also show the number of transmissions for different values of L_w, t_m and p_m and then compare them. Figures 14(a), (b) and (c) show the numbers of transmissions for $t_m = 1200$ s, 1800 s and 3600 s, respectively, where $p_m = 0.5$ and $t_e = 1800$ s. Figures 15(a) and (b) show those for $p_m = 0.2$ and 0.0, respectively, where $t_m = 3600$ s and $t_e = 1800$ s. In these figures, we show the number of transmissions recorded every 300 seconds.



(a) $p_m = 0.2$.

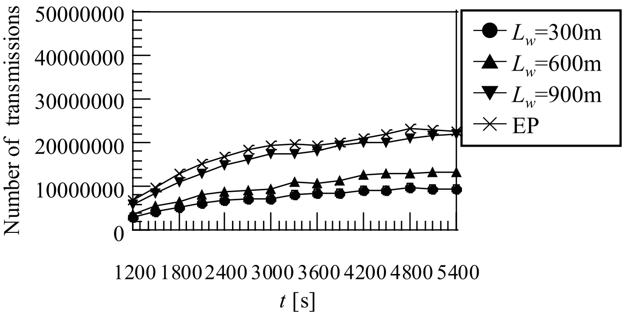


(b) $p_m = 0.0$.

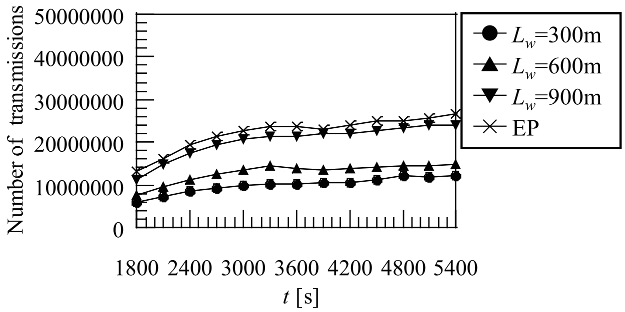
Fig. 13 Success ratio of navigation, where $t_m = 3600$ s and $t_e = 1800$ s.

As mentioned, it is not easy to make a fair comparison of the number of transmissions between EP and FST. Therefore, we set the value of the rate of departures of nodes with guidance as $(1 - p_{fail})(1 - p_m)\lambda$ in the simulations of EP. In each figure, we show the data of FST for three values of L_w. We compare EP with FST for $L_w = 900$ m because the success ratio for $L_w = 900$ m is the best among the three values of L_w as discussed above. Hence, as the value of p_{fail}, we compute p_{fail} of FST for $L_w = 900$ m by computer simulation. For Fig. 14(a), p_{fail} is obtained by computer simulation of FST for $L_w = 900$ m, where $t_m = 1200$ s, $p_m = 0.5$ and $t_e = 1800$ s, and the result of p_{fail} is 0.0310. In the same manner, we compute p_{fail} of FST for $L_w = 900$ m in Figs. 14(b) and (c) and Fig. 15. The results are $p_{fail} = 0.0300$ and 0.0232 in Figs. 14(b) and (c), respectively. For Figs. 15(a) and (b), $p_{fail} = 0.0261$ and 0.0301, respectively.

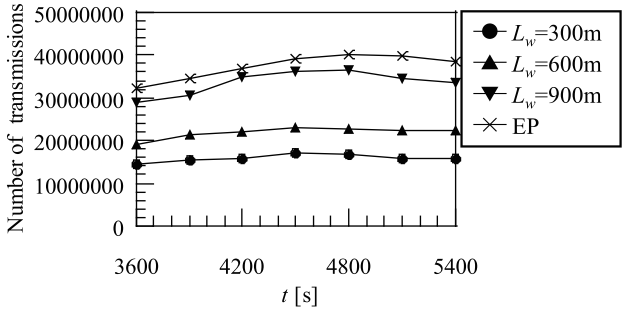
In Figs. 14 and 15, we can confirm that the number of transmissions increases as L_w increases. This is because IF improves and tends to continue longer as L_w increases as discussed above. Figures 12(c) and 14(c) are the results for the same set of parameters but show another tendency. In Fig. 12(c), the success ratios of EP and FST for the three values of L_w are high and close to each other. In Fig. 14(c), however, the number of transmissions rapidly decreases as L_w decreases. This shows that we can have a value of L_w that decreases the number of transmissions while keeping the suc-



(a) $t_m = 1200$ s.

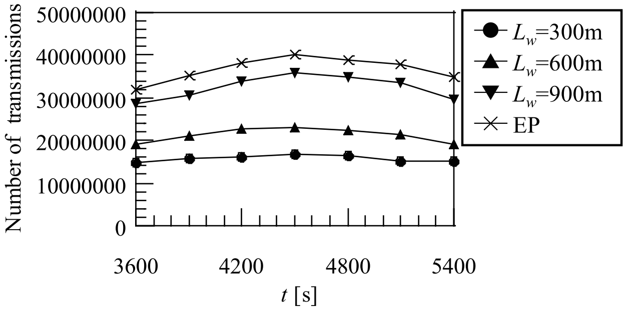


(b) $t_m = 1800$ s.

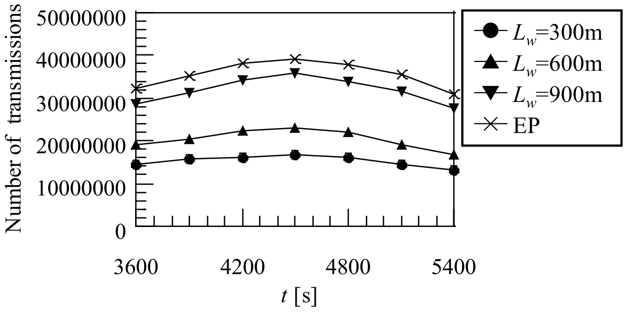


(c) $t_m = 3600$ s.

Fig. 14 Number of transmissions, where $p_m = 0.5$ and $t_e = 1800$ s.



(a) $p_m = 0.2$



(b) $p_m = 0.0$

Fig. 15 Number of transmissions, where $t_m = 3600$ s and $t_e = 1800$ s.

cess ratio sufficiently high. These results demonstrate that the proposed method's route guidance performance is close to that of EP while decreasing the number of transmissions. This is an important advantage of FST compared with EP.

Next, we compare the number of transmissions for different values of t_m. As t_m becomes larger, the success ratio and the amount of accumulated data becomes larger as mentioned. Accordingly, the number of transmissions is expected to be larger. This tendency can be seen in Figs. 14(a), (b) and (c). Furthermore, the success ratios for $p_m = 0.5, 0.2, 0.0$ in Fig. 12(c) and Figs. 13(a) and (b) have almost the same tendency. Therefore, the numbers of transmissions also have similar tendencies for $p_m = 0.5, 0.2, 0.0$.

In this paper, we set the position and size of the TA in advance. As can be seen from the results, however, an appropriately sized TA is required. Consequently, we need dynamic control of the TA to achieve an appropriate TA size. Dynamic TA control has been previously studied [15], [18], and it is applicable to FST. Therefore, we leave the application of dynamic TA control to FST as a future issue to be explored.

4. Conclusions

In this paper, we proposed applying IF to sensor networking. In this application, we use a new capability of IF, called Floating Storage (FST), to accumulate data virtually in and around a transmittable area (TA) without needing any gateway for storing data, which is required in conventional sensor networks. In addition, FST does not need any communication infrastructure (i.e., cellular networks) at all. We also proposed using FST to develop and share available routes in disaster situations when some of the road network links become unavailable and people do not have information on the link failures.

The proposed method differs from conventional IFs in that it shares multiple types of data, whereas typical IFs share just one type of data. The proposed method thus needs to manage the increased amount of data accumulated in and around the TA. With the proposed method, the data stored by FST disappear due to the local expiration of IF, but these data suddenly and rapidly accumulate again because they are transported back by nodes that accumulated them in other parts of the TA. Furthermore, for application to finding available routes, we have to assign the role of developing new routes to certain mobile nodes according to a time schedule.

Considering these key properties of FST, we evaluated the performance of the proposed method by computer simulation. We evaluated how FST accumulates data while considering the differences due to place and time. The results confirm that the proposed method successfully accumulates a sufficient amount of data over the service area and can respond to a sudden dissipation of data.

We also evaluated the performance of route guidance using the data accumulated by FST. We showed that the proposed method's performance is good and close to that of EP, while also reducing the number of transmissions required.

As mentioned above, we used some assumptions on the positioning and wireless communication in the computer simulations because we focused on the effects of node mobility on performance, since IF's performance largely depends on how mobile nodes pass each other and behave between the TAs. Considering additional, more complicated factors in the performance evaluation is an important future focus. Furthermore, we must apply dynamic control of the TA to FST to achieve autonomous and distributed FST operation. Dynamic control of p_m and theoretical analysis of FST are important future issues.

Acknowledgments

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