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A Node Deployment Strategy for Efficient Sensing with Mobile Sensors in Sparse Sensor Networks

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In this paper, we propose an extended method of our previous mobile sensor control method, named DATFM (Data Acquisition and Transmission with Fixed and Mobile node). DATFM uses two types of sensor nodes, *fixed node* and *mobile node*. The data acquired by nodes are accumulated on a fixed node before being transferred to the sink node. The extended method, named DATFM/DF (DATFM with deliberate Deployment of Fixed nodes), strategically deploys sensor nodes based on the analysis of the performance of DATFM in order to improve the efficiency of sensing and data gathering. We also conduct simulation experiments to evaluate the performance of DATFM/DF.

1. Introduction

Recent advances in wireless communication technology has led to an increasing interest in wireless sensor networks. The capability to construct large-scale sensing systems with integrated multiple sensor modes operation makes it likely that wireless sensor networks will be applied to many applications including environmental monitoring, eco-system investigation, and building management.

Here, there are some applications where it is difficult to deploy a large number of sensor nodes such as disaster sites, planetary exploration, polluted areas, and underwater environments^{1),2)}. In such environments, deployment of sensor nodes becomes too sparse to achieve sufficient sensing and data transfer. For example, in planetary or underwater exploration, a large number (e.g., hundreds or thousands) of nodes cannot be deployed because of space and cost constraints. Moreover, in a polluted plant, the sensing region is too large to deploy a suffi-

cient number of nodes. Although some studies assume applications where a large number of nodes are deployed from the air (e.g., from airplanes or helicopters), such deployment becomes impossible in a building or under the heap of ruins. Furthermore, long range radio waves cannot improve the connectivity in these applications, since they are affected by the ambient surrounding such as obstacles and landscape.

On the other hand, with the development of robotics technology in recent years, there have been many studies on sensor nodes with a moving facility (mobile sensors). Mobile sensors are well suited for a sparse network since a large region can be monitored with a small number of sensor nodes. In this paper, we call wireless sensor networks which fully or partially include mobile sensors *mobile sensor networks*.

Until now, we proposed DATFM (Data Acquisition and Transmission with Fixed and Mobile node)³⁾, which is an effective mobile sensor control method for sparse sensor networks to achieve effective sensing and data transfer. DATFM uses two types of sensor nodes, *fixed node* and *mobile node*. A fixed node has two roles, temporarily accumulating data acquired by nodes and constructing a communication route between fixed nodes for transmitting the accumulated data. By using fixed nodes, DATFM can effectively control the behavior of mobile nodes, and thus, effective sensing and data transfer can be achieved even in a sparse network.

Here, since each fixed node in DATFM accumulates data generated in its vicinity, the performance of sensing depends on the locations of fixed nodes. In addition, since the distances between fixed nodes affect the delay in constructing a communication route, data transfer performance also depends on the locations of fixed nodes. In this paper, we analyze the effects of the deployment of fixed nodes on the performance and propose a deliberate deployment strategy to improve the performance. We call the method to which the above strategy is applied DATFM/DF (DATFM with deliberate Deployment of Fixed nodes).

The remainder of this paper is organized as follows. In Section 2, we briefly present the system model assumed in this paper and conventional data transfer methods in mobile sensor networks. In Section 3, we explain our previous method, DATFM. In Section 4, we present DATFM/DF, which is proposed

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in this paper. In Section 5, we present the results of simulation experiments. Finally, we conclude this paper in Section 6.

2. System Model and Related Work

2.1 System Model

In this paper, we assume an application which monitors a vast region with a small number of nodes. For example, in an investigation of the ocean floor or a planet, detection of the mineral veins or undiscovered resources in an unexplored area, and observation of the toxic gas in a disaster site, a vast region must be monitored by a small number of nodes. To monitor the whole region with a small number of nodes, mobile sensors are introduced into the network. In addition, we assume that each sensor acquires data whose sizes are relatively large such as pictures or movies. Moreover, we assume that the capacity of storage in each sensor node is relatively small. This is because storage media is well known to be prone to breakdowns due to several effects such as radiation in some hazardous environments such as planetary exploration⁴⁾.

The data acquired by sensor nodes are transferred to the sink node similar to the assumption in many conventional works. Each node has a unique identifier in the network. In addition, we assume that all nodes have the same sensor and radio devices. Thus, the sensing and wireless communication ranges are the same among all nodes. Following the conventional works^{5)–12)}, we assume that there are no obstacles in the region.

2.2 Related Work

There are some works on route construction in mobile sensor networks. In Ref. 5), the authors proposed a method to determine the behaviors of mobile sensors. In this method, each mobile sensor determines with a certain probability or whether it acquires data or transmits data. In the latter case, the sensor moves to construct a communication route between the sink node and a sensor that determines to transmit data. In Ref. 7), each mobile sensor periodically sends information on its location to nearby sensors. Using this information, each mobile sensor predicts the locations of other sensors in the future and selects a mobile sensor to send the data. In Ref. 13), the authors proposed a cluster-based data gathering method which divides a region into several zones and clusters

mobile sensors based on the divided zones. In each zone, a mobile sensor is elected as the cluster head of the zone. The cluster head collects data acquired in the corresponding zone, and transmits the collected data toward the sink node via communication routes between cluster heads of adjacent zones. Another data transfers method divides the region into multiple areas in Ref. 14). In this method, mobile sensors exchange their past moving paths with each other. From the exchanged information, each sensor predicts the area to which each nearby sensor will move in the future. When a mobile sensor wants to transfer data to an area, it forwards the data to a nearby sensor that is expected to the destination. In Ref. 15), the authors proposed a data transfer method between mobile sensors with predetermined mobility. This method assumes that the moving path of every mobile sensor is predetermined and known by all other sensors. Using information on moving paths of other mobile sensors, each sensor selects a mobile sensor to which it forwards its holding data. These methods do not work in a sparse network because it becomes difficult to construct a communication route due to the poor connectivity between mobile sensors.

In Refs. 11) and 12), a data transfer method in mobile sensor networks has been proposed. In this method, mobile sensors are classified into two types of nodes, mobile sensor nodes and high-end sink nodes. Each mobile sensor node acquires data and sends it to a nearby high-end sink node by flooding. After that, the high-end sink node directly transmits the received data to the sink node. In Ref. 6), the authors proposed a method that introduces broadcast system. In this method, the sink node broadcasts the locations of all mobile sensors that connect with itself. By using this information, each mobile sensor adjusts its moving destination in order to decrease its moving distance for transferring its acquired data. These methods need some special nodes or devices for transferring data to the sink node. It is therefore difficult to apply these methods to the assumed environments.

On the other hand, several data transfer method without any special equipment have been proposed^{8)–10),16)}. In these methods, each mobile sensor basically transfers data by moving to the sink node. Thus, in a vast region, data acquisition and transfer efficiency declines due to the increase of moving distance.

There is another kind of research in which vehicles become mobile sensors in

road-to-vehicle communication system¹⁷⁾. In this research, each vehicle manages its transmission buffer considering the short connection time with a road-side access point. Specifically, each vehicle evaluates the importance of each data acquired by itself, and changes the order of transmission in its buffer. This research focuses on the data management in each mobile sensor. However, it assumes road-to-vehicle communication systems, which are different from our assumed environment.

3. DATFM: Our Previous Method

In this section, we present our previous method, DATFM (Data Acquisition and Transmission with Fixed and Mobile node)³⁾.

3.1 Assumptions

In DATFM, there are two types of sensor nodes, fixed node and mobile node (the sink node is classified as a fixed node). Each node acquires its present location by using GPS or other location detection methods^{18),19)}. Moreover, all nodes know the locations of all fixed nodes.

3.1.1 Fixed Node

A fixed node does not move. It has larger memory space compared with a mobile node and accumulates data acquired by itself and other nodes. In addition, it controls nearby mobile nodes to construct a communication route when transmitting the accumulated data toward the sink node.

DATFM divides the region into several areas based on a Voronoi diagram in which fixed nodes are the site points. Here, the Voronoi diagram of a set of points partitions the region into convex polygons that consist of the vertical bisectors of the points. Every point in a polygon is closer to the site point in the corresponding polygon than to any other site points. In DATFM, each fixed node has charge of the corresponding area. In other words, each fixed node has a role for collecting data acquired in the area it exists. We call the area for each fixed node as its *territory*. **Figure 1** shows an example of Voronoi diagram and divided territories. Furthermore, each fixed node determines the sensing points of mobile nodes that are to perform sensing operation in its territory.

3.1.2 Mobile Node

A mobile node moves around the region. In addition, it has the following three

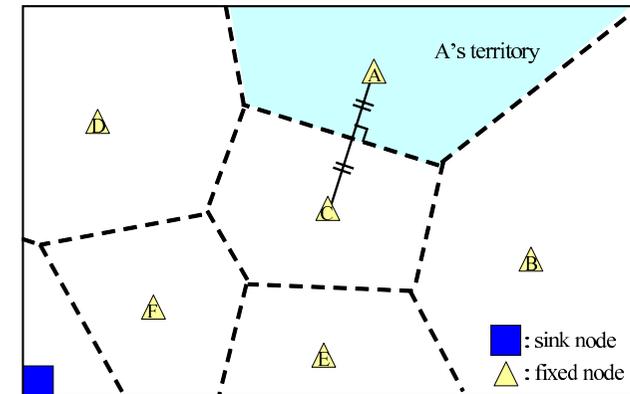


Fig. 1 Dividing the region.

modes:

Sensing mode (SM): A node selects a territory to perform sensing and moves there. After performing the sensing operation in the territory, it determines new territory to move to.

Collecting mode (CM): When a node in *SM* receives a *route request packet (RReq)* from a fixed node, it changes its mode into *collecting mode (CM)*. In *CM*, a node moves faster than that in *SM* in order to collect other mobile nodes to construct a communication route.

Transmission mode (TM): When a node in *SM* receives a *route construction request packet (RCReq)* from a fixed node or a mobile node in *CM*, it changes its mode into *transmission mode (TM)*. In *TM*, a node constructs a route and transfers the data.

3.2 Moving Strategy of Mobile Nodes

A mobile node basically sets its mode as *SM*. It selects a territory to perform sensing according to the probability which is proportional to the size of each territory. After that, it moves to the territory by the following steps:

- (1) It moves to connect to the nearest fixed node (i.e., the fixed node in the current territory) and transmits its acquired data.
- (2) It calculates the distances between the fixed node in the selected territory and all those in the territories adjacent to the currently territory and moves

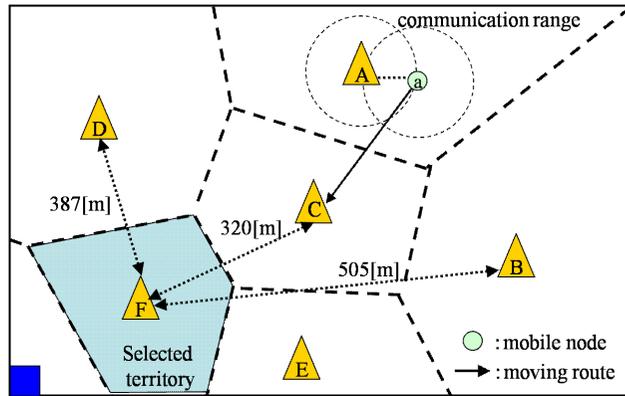


Fig. 2 Selection of the next node to move.

to the fixed node that is the nearest to fixed node in the selected territory. **Figure 2** shows an example to choose the next fixed node to move to. After transmitting its acquired data to fixed node *A*, mobile node *a* calculates the distances between fixed node *F* that has charge of the selected territory and fixed nodes *B*, *C*, and *D*, which are adjacent to the current territory. After that, it chooses fixed node *C* that is the nearest to fixed node *F* and moves there. This procedure is repeated until the mobile node connects to the fixed node in the selected territory.

- (3) It receives the information of the sensing point from the fixed node. Then it moves there and performs the sensing operation.

3.3 Data Transmission

A fixed node starts to transfer the accumulated data when the amount of the accumulated data in its memory exceeds the predetermined threshold.

First, the fixed node (the *source* node) selects the adjacent fixed node which is the nearest to the sink as the next fixed node to transfer the data (the *destination* node). Here, we define the transmission route from source node to the destination node as the *route*. Next, the source node sends a *RReq* to a mobile node that first of all connects to itself. The mobile node that receives the *RReq* changes its mode into *CM*.

The mobile node in *CM* visits the adjacent fixed nodes and requests them to

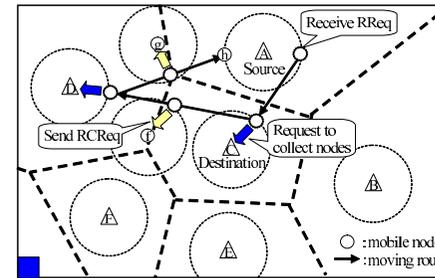


Fig. 3 Collecting mobile nodes.

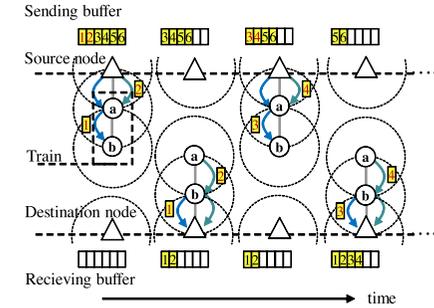


Fig. 4 Train transmission.

collect mobile nodes to construct a communication route. After that, it returns to the source node and changes its mode into *TM*. Moreover, when the mobile node in *CM* connects to other mobile nodes while moving, it sends a *route construction request (RCReq)* to the connected nodes. If the mobile node that receives the *RCReq* is in *SM*, it moves to the source node and changes its mode into *TM*. For example in **Fig. 3**, on receiving a *RReq* from the source node *A*, the mobile node *h* moves to fixed nodes *C* and *D*, and requests them to collect mobile nodes. After that, it returns to *A* and changes its mode into *TM*. In addition, *h* sends *RCReqs* to the connected mobile nodes *f* and *g* while moving. When a mobile node in *SM* connects to the source node or a fixed node which received the request from the mobile node in *CM*, the source node or the fixed node sends a *RCReq* to the connected mobile node. The mobile node which receives the *RCReq* moves to the source node and changes its mode into *TM*.

The source node starts data transmission when it first connects to a mobile node in *TM*. Here, when the number of collected mobile nodes is smaller than the required number of mobile nodes for constructing the communication route (N_{req}), the source node transfers the data by using *train transmission*. In train transmission, the collected mobile nodes form the line segment (train). The data are transferred by the movement and communication of the formed train as shown in **Fig. 4**. When another mobile node in *TM* connects the source node, the source node adds the connected node to the train until the completed communication route is constructed.

4. DATFM/DF

DATFM achieves the effective data acquisition and transmission by accumulating data on a fixed node and transferring the accumulated data by using multiple mobile nodes. Here, further improvement of the effectiveness of DATFM is expected in an environment where fixed node can be strategically deployed. This idea comes from the following two features of DATFM:

- Since each fixed node accumulates data generated in its territory, the sizes of territories affect the sensing performance.
- Since each fixed node transfers the accumulated data by using multiple mobile nodes, the route distances (between source and destination nodes) affect the performance of data transmission.

Therefore, we analyze the effects of the locations of fixed nodes, and propose a deliberate deployment strategy, named DATFM/DF (DATFM with deliberate Deployment of Fixed nodes), to further improve the effectiveness.

4.1 Analysis of Effects of the Deployment of Fixed Nodes

In this analysis, we discuss the *sensing rate* R_{sense} , which is defined as the number of sensing operations per unit time in the whole region. The sensing rate depends on the time for each mobile node to move to its sensing point.

4.1.1 Assumption

Before starting the analysis, we show the assumed environment in this section. We do not consider the concepts of collection of mobile nodes by using mobile node in *CM* described in Section 3.3 for simplicity. In addition, the moving path of a mobile node to the selected territory described in Section 3.2 can be roughly approximated as a straight line. Therefore, we assume that mobile nodes do not go through fixed nodes in the adjacent territories.

We assume that the parameters in **Table 1** are given. Moreover, we define the following two cycles:

- The *sensing cycle* is the sequence of a sensing operation, in which a mobile node departs from a fixed node, moves to the next sensing point, performs the sensing operation, and moves to the nearest fixed node (see **Fig. 5**). We also define the *average sensing cycle time* T_{sense} as the average time elapsed for a sensing cycle.

Table 1 Given parameters in the analysis.

Parameter	Description
i	IDs of fixed nodes.
\mathbf{L}_i	location of fixed node i .
\mathbf{T}_i	territory of fixed node i .
\mathbf{d}_i	location of the sensing point in \mathbf{T}_i (i.e., $\mathbf{d}_i \in \mathbf{T}_i$).
\mathbf{S}_F	set of fixed nodes in the whole region.
S_{region}	size of the whole region (i.e., $S_{region} = \sum_i \mathbf{T}_i $).
ν_m	velocity of mobile nodes in <i>SM</i> .
ν_r	velocity of mobile nodes in <i>TM</i> .
T_{acq}	time for a sensing operation.
N_{mov}	number of mobile nodes in the whole region.
N_{fix}	number of fixed nodes in the whole region.
D	data size acquired in a sensing operation.
r_{com}	communication range of all nodes.
Th	threshold for starting data transmission.

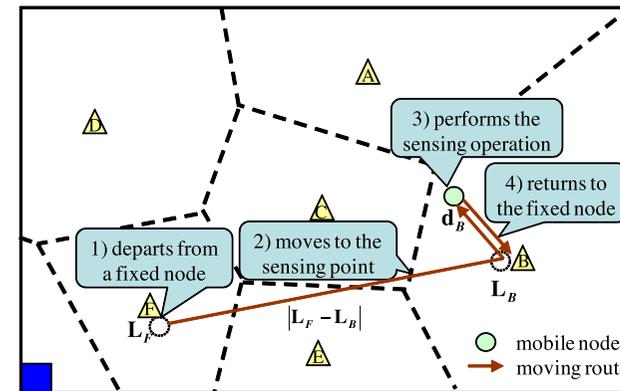


Fig. 5 Operations in a sensing cycle.

- The *transfer cycle* is the sequence of a data transmission, in which a fixed node accumulates data and transmits the accumulated data to the destination node. We also define the *average transfer cycle time* $T_{transfer}$ as the average time elapsed for a transfer cycle.

4.1.2 Analysis of R_{sense}

First, R_{sense} is calculated as the inverse of T_{sense} . As an example, we assume a mobile node in **Fig. 5** which departs from fixed node F and performs the sensing

operation in \mathbf{T}_B . First, since the distance between fixed nodes F and B is $|\mathbf{L}_F - \mathbf{L}_B|$ and that between fixed node B and the sensing point is $|\mathbf{d}_B - \mathbf{L}_B|$, the total time elapsed of the sensing cycle becomes $|\mathbf{L}_F - \mathbf{L}_B|/\nu_m + T_{acq} + 2 \cdot |\mathbf{d}_B - \mathbf{L}_B|/\nu_m$. Here, when the fixed node controls the sensing point in order for all of its territory to be its territory to be monitored uniformly, the average elapsed time for moving between \mathbf{L}_B and \mathbf{d}_B becomes the average of the moving time from \mathbf{L}_B to any location in \mathbf{T}_B . Moreover, since the probability that a mobile node selects a territory to perform sensing depends on the size of the territory, the average time which a mobile node departs from any fixed node (other than B) and moves to fixed node B becomes $\sum_{j \in \mathbf{S}_F, j \neq B} (|\mathbf{T}_j|/S_{region}) \cdot (|\mathbf{L}_j - \mathbf{L}_B|/\nu_m)$.

Therefore, the average sensing cycle time of a mobile node that performs sensing operation in \mathbf{T}_i (T_{sense_i}) is derived by the following equation:

$$T_{sense_i} = \sum_{j \in \mathbf{S}_F, j \neq i} \frac{|\mathbf{T}_j|}{S_{region}} \cdot \left(\frac{|\mathbf{L}_i - \mathbf{L}_j|}{\nu_m} \right) + T_{acq} + 2 \cdot \frac{ave(|\mathbf{d}_i - \mathbf{L}_i|)}{\nu_m}. \quad (1)$$

Here, the average sensing cycle time in the whole region (T_{sense}) is derived by the average of the T_{sense_i} for all i . Thus,

$$T_{sense} = \sum_{i \in \mathbf{S}_F} \frac{|\mathbf{T}_i|}{S_{region}} \cdot T_{sense_i}. \quad (2)$$

After fixed node i accumulates data, it starts a data transmission. During the data transmission, the mobile nodes which construct the communication route cannot perform the sensing operation. Thus, we should consider the frequency of data transmissions (R_{route}), and the number of mobile nodes used for data transmission.

Let us define the average number of free nodes N_{free} that are not used for data transmission in unit time. Then, R_{sense} is represented by using the ratio of free nodes to all mobile nodes per one average sensing cycle time, that is, $(N_{free}/N_{mov}) \cdot (1/T_{sense})$.

N_{free} can be represented by using the required number of mobile nodes to construct a communication route N_{req} and the frequency of data transmission R_{route} , that is,

$$N_{free} = N_{mov} - \sum_{i \in \mathbf{S}_F} (R_{route_i} \cdot N_{req_i}). \quad (3)$$

Therefore, R_{sense} is represented by the following equation:

$$R_{sense} = \frac{1}{T_{sense}} \cdot \left(1 - \frac{\sum_{i \in \mathbf{S}_F} (R_{route_i} \cdot N_{req_i})}{N_{mov}} \right). \quad (4)$$

In the above equations, N_{req_i} is the required number of mobile nodes for the data transmission from fixed node i , which is represented by $|\mathbf{L}_i - \mathbf{L}_d|/r_{com}$ where \mathbf{L}_d is the location of the destination node of the data transmission.

The frequency of route constructions in fixed node i (R_{route_i}) is the ratio of times elapsed for data transmission ($T_{transmit_i}$) to the average transfer cycle time ($T_{transfer_i}$), that is, $T_{transmit_i}/T_{transfer_i}$. $T_{transfer_i}$ is the sum of times elapsed for accumulating data (T_{acc_i}) and data transmission. T_{acc_i} is derived by using the required number of times that fixed node i connects to mobile nodes which hold data, and the average time for each mobile node to connect to fixed node i (T_{ave_i}). The former is represented as Th/D . The latter is represented as the product of average sensing cycle time and the inverse of the number of mobile nodes that exist in this territory ($N_{mov} \cdot |\mathbf{T}_i|/S_{region}$). Therefore, T_{acc_i} is represented by the following equation:

$$T_{acc_i} = \frac{Th}{D} \cdot T_{ave_i} = \frac{Th}{D} \cdot \frac{S_{region} \cdot T_{sense_i}}{N_{mov} \cdot |\mathbf{T}_i|}. \quad (5)$$

$T_{transmit_i}$ is the total time from when fixed node i starts data transmission until the accumulated data are transferred to the destination. Here, we define the *round* as a sequence of operations in a data transmission, that is, the train departs from the source node, moves to the destination, transmits data, and returns to the source node. We assume that the first round is conducted by the train that contains one mobile node. The elapsed time for this round ($T_{train_{i_1}}$) becomes $2 \cdot (|\mathbf{L}_i - \mathbf{L}_j| - 2 \cdot r_{com})/\nu_r$. The number of mobile nodes which newly connect to fixed node i during this round ($N_{train_{i_1}}$) is $T_{train_{i_1}}/T_{ave_i}$. Thus, in the second round, the train transmission is conducted by $N_{train_{i_1}} + 1$ mobile nodes. The elapsed time for this round is represented by the following equation:

$$\begin{aligned}
 T_{train_{i_2}} &= \frac{2 \cdot \left(|\mathbf{L}_i - \mathbf{L}_j| - r_{com} \cdot \left(2 + \frac{T_{train_{i_1}}}{T_{ave_i}} \right) \right)}{\nu_r} \\
 &= A \cdot T_{train_{i_1}} \cdot \left(A = 1 - \frac{2 \cdot N_{mov} \cdot |\mathbf{T}_i| \cdot r_{com}}{\nu_r \cdot S_{region} \cdot T_{sense_i}} \right) \quad (6)
 \end{aligned}$$

In the same way, the elapsed time for N -th round ($T_{train_{i_N}}$) is represented by the following equation:

$$\begin{aligned}
 T_{train_{i_N}} &= \frac{2 \cdot \left(|\mathbf{L}_i - \mathbf{L}_j| - r_{com} \cdot (2 + N_{train_{N-1}}) \right)}{\nu_r} \\
 &= A^{N-1} \cdot T_{train_{i_1}}. \quad (7)
 \end{aligned}$$

Therefore, when a data transmission is conducted by N rounds, $T_{transmit_i}$ is derived by the following equation:

$$\begin{aligned}
 T_{transmit_i} &= T_{train_{i_1}} + T_{train_{i_2}} + \cdots + T_{train_{i_N}} \\
 &= T_{train_{i_1}} + A \cdot T_{train_{i_1}} + \cdots + A^{N-1} \cdot T_{train_{i_1}} \\
 &= \frac{(1 - A^{N-1}) \cdot T_{train_{i_1}}}{(1 - A)}. \quad (8)
 \end{aligned}$$

Here, since the required time for transferring data between connected nodes is much smaller than that for moving between fixed nodes, we can ignore the time elapsed for transferring data after constructing the complete communication route. Thus, we suppose $T_{transmit_i}$ is equal to the time after starting the first round until the communication route is constructed. Here, as shown in Eq. (6), A is smaller than 1. In addition, since we assume a sparse network environment, N tends to be large. Thus, we assume that $A^{N-1} \approx 0$ and $T_{transmit_i}$ can be represented by the following equation:

$$T_{transmit_i} \approx \frac{T_{train_{i_1}}}{1 - A} = \frac{T_{train_{i_1}} \cdot \nu_r \cdot T_{sense_i} \cdot S_{region}}{2 \cdot r_{com} \cdot N_{mov} \cdot |\mathbf{T}_i|}. \quad (9)$$

From the above discussions, R_{route_i} is represented by the following equation:

$$\begin{aligned}
 R_{route_i} &= \frac{\frac{T_{train_{i_1}} \cdot \nu_r \cdot T_{sense_i} \cdot S_{region}}{2 \cdot r_{com} \cdot N_{mov} \cdot |\mathbf{T}_i|}}{\frac{T_h}{D} \cdot \frac{S_{region} \cdot T_{sense_i}}{N_{mov} \cdot |\mathbf{T}_i|} + \frac{T_{train_{i_1}} \cdot \nu_r \cdot T_{sense_i} \cdot S_{region}}{2 \cdot r_{com} \cdot N_{mov} \cdot |\mathbf{T}_i|}} \\
 &= \frac{T_{train_{i_1}} \cdot \nu_r}{(T_{train_{i_1}} \cdot \nu_r) + \left(2 \cdot r_{com} \cdot \frac{T_h}{D} \right)}. \quad (10)
 \end{aligned}$$

4.2 Guideline for Deploying Fixed Node

It is impossible to derive the optimal locations of fixed nodes directly from the result of the analysis, i.e., Eq. (4). This is because the aim of the analysis of the sensing rate R_{sense} itself is not to derive the optimal locations of fixed nodes but to derive the effects of the locations of fixed nodes. Thus, the equations in the analysis are based not only on the locations of fixed nodes but on other parameters that indirectly depend on the locations of fixed nodes. Specifically, as shown in Table 1, some given parameters for the analysis such as \mathbf{T}_i and \mathbf{d}_i depend on the locations of fixed nodes. In addition, the distance between fixed nodes $|\mathbf{L}_i - \mathbf{L}_j|$ appears in the result of the analysis. This value also indirectly depends on the locations of fixed nodes.

Thus, we first extracted the abstract guidelines from the result of the analysis in order to make it easier to determine the locations of fixed nodes.

From Eq. (4), we can see that R_{sense} depends on the total of required numbers of mobile nodes to construct a communication route ($\sum_{i=0}^{N_{fix}} N_{req_i}$) and the average sensing cycle time (T_{sense}).

First, from Eqs. (1) and (2), T_{sense} is represented by the following equation:

$$\begin{aligned}
 T_{sense} &= \sum_{i=0}^{N_{fix}} \frac{|\mathbf{T}_i|}{S_{region}} \left(\frac{2 \cdot ave(|\mathbf{L}_i - \mathbf{d}_i|)}{\nu_m} \right. \\
 &\quad \left. + \sum_{j=0, j \neq i}^{N_{fix}} \frac{|\mathbf{T}_j|}{S_{region}} \cdot \frac{|\mathbf{L}_i - \mathbf{L}_j|}{\nu_m} \right) + T_{acq}. \quad (11)
 \end{aligned}$$

This equation indicates that, T_{sense} depends on the average distance between \mathbf{L}_i and \mathbf{d}_i ($ave(|\mathbf{L}_i - \mathbf{d}_i|)$), the size of each territory ($|\mathbf{T}_i|$), and the distance between fixed nodes ($|\mathbf{L}_i - \mathbf{L}_j|$). The smaller these parameters are, the smaller T_{sense} becomes.

First, in order to decrease $ave(|\mathbf{L}_i - \mathbf{d}_i|)$, we suppose that, the location of a fixed node should be the center of the corresponding territory.

Next, we discuss the way to minimize the value of $\sum_{i=0}^{N_{fix}} (|\mathbf{T}_i| \cdot ave(|\mathbf{L}_i - \mathbf{d}_i|))$. Since $ave(|\mathbf{L}_i - \mathbf{d}_i|)$ depends on $|\mathbf{T}_i|$, we can regard $ave(|\mathbf{L}_i - \mathbf{d}_i|)$ as a function of $|\mathbf{T}_i|$. Here, we regard $ave(|\mathbf{L}_i - \mathbf{d}_i|)$ as proportional to $|\mathbf{T}_i|$ for simplicity. Thus, we can express the value as $\sum_{i=0}^{N_{fix}} (\beta |\mathbf{T}_i|^2)$. In order to minimize this value, we discuss the partial differentiation of $\sum_{i=0}^{N_{fix}} |\mathbf{T}_i|^2$ with respect to $|\mathbf{T}_i|$. First, we differentiate partially with respect to $|\mathbf{T}_0|$.

$$\frac{\partial}{\partial |\mathbf{T}_0|} \sum_{i=0}^{N_{fix}} (|\mathbf{T}_i|^2) = \frac{\partial}{\partial |\mathbf{T}_0|} (|\mathbf{T}_0|^2 + |\mathbf{T}_1|^2 + \cdots + |\mathbf{T}_{N_{fix}}|^2). \quad (12)$$

Here, since $|\mathbf{T}_i|$ can be expressed as $S_{region} - \sum_{j=0, j \neq i}^{N_{fix}} |\mathbf{T}_j|$, the partial differentiation of $|\mathbf{T}_i|^2$ can be expressed as $2 \cdot (S_{region} - \sum_{j=0, j \neq i}^{N_{fix}} |\mathbf{T}_j|)$. Therefore,

$$\begin{aligned} \frac{\partial}{\partial |\mathbf{T}_0|} \sum_{i=0}^{N_{fix}} (|\mathbf{T}_i|^2) &= |\mathbf{T}_0| - (N_{fix} - 1) \cdot S_{region} + (N_{fix} - 1) \cdot |\mathbf{T}_0| \\ &\quad + (N_{fix} - 2) \cdot S_{region} \\ &= N_{fix} \cdot |\mathbf{T}_0| - S_{region}. \end{aligned} \quad (13)$$

In order to minimize this value, $|\mathbf{T}_0|$ should be S_{region}/N_{fix} . In the same way, we can derive $|\mathbf{T}_i|$ for all $i = \{0, 1, \dots, N_{fix}\}$ as the same value S_{region}/N_{fix} . Therefore, considering when the location of a fixed node is the center of the corresponding territory, we can derive the guideline: *The distance between fixed nodes on each communication route and the territory size of each fixed node should be uniform (Guideline 1).*

Next, in order to decrease $\sum_{i=0}^{N_{fix}} \sum_{k=0, k \neq i}^{N_{fix}} |\mathbf{L}_i - \mathbf{L}_k|$, the distance between fixed nodes should be small. This term represents the moving distance of a mobile node from the connected fixed node to the fixed node that has charge of the next sensing point. Since each mobile node in DATFM goes through the fixed nodes of adjacent territories until arriving at the territory which contains the next sensing point, we can derive the following guideline: *The total length of moving paths of mobile nodes between all pairs of fixed nodes should be small (Guideline 2).*

Next, we discuss the relation between N_{mov} and $\sum_{i=0}^{N_{fix}} R_{route_i} \cdot N_{req_i}$. From Eq. (3), the ratio of free nodes to all mobile nodes is represented by the following equation:

$$\frac{N_{free}}{N_{mov}} = 1 - \frac{\sum_{i=0}^{N_{fix}} R_{route_i} \cdot N_{req_i}}{N_{mov}}. \quad (14)$$

When this value becomes lower than zero, not all mobile nodes can perform sensing operations, and thus, the network does not work. Therefore, the value must be larger than zero. Here, in the data transmission from fixed node i to j , $|\mathbf{L}_i - \mathbf{L}_j|$ can be expressed as $(N_{req_i} + 1) \cdot r_{com}$. Therefore, from Eq. (11) we can derive the following equation:

$$R_{route_i} = \frac{2 \cdot (N_{req_i} - 1) \cdot r_{com}}{(2 \cdot (N_{req_i} - 1) \cdot r_{com}) + (2 \cdot r_{com} \cdot \frac{Th}{D})} \approx \frac{N_{req_i}}{N_{req_i} + \frac{Th}{D}}. \quad (15)$$

Thus,

$$\sum_{i=0}^{N_{fix}} R_{route_i} \cdot N_{req_i} = \sum_{i=0}^{N_{fix}} \frac{N_{req_i}^2}{N_{req_i} + \frac{Th}{D}}. \quad (16)$$

Here, if Guideline 1 is satisfied, N_{req_i} becomes uniform among all i -s. Thus,

$$\sum_{i=0}^{N_{fix}} R_{route_i} \cdot N_{req_i} = \frac{N_{fix} \cdot N_{req_i}^2}{N_{req_i} + \frac{Th}{D}}. \quad (17)$$

In order for N_{free}/N_{mov} to be larger than zero,

$$\begin{aligned} N_{move} &> \frac{N_{fix} \cdot N_{req_i}^2}{N_{req_i} + \frac{Th}{D}} \\ \frac{N_{move} - P}{2 \cdot N_{fix}} &< N_{req} < \frac{N_{move} + P}{2 \cdot N_{fix}} \\ &\left(P = \sqrt{N_{move}^2 + 4 \cdot N_{fix} \cdot N_{move} \cdot \frac{Th}{D}} \right) \end{aligned} \quad (18)$$

Let us define the right-hand-side term in Eq.(18) as N_{max} . From the above equation, we can derive the guideline: *The required number of mobile nodes to construct the communication route from each fixed node should be smaller than N_{max} (Guideline 3).*

However, if we follow Guidelines 2 and 3, most fixed nodes are deployed near the sink node. This may violate Guideline 1. Therefore, we should set the following guideline in order to suppress such an undesirable increase in the difference in territory sizes: *Some fixed nodes should be deployed at locations which are far from the sink node with high priority (Guideline 4).*

From the analysis, we can see that some guidelines can be derived intuitively from the results of the analysis. For example, Eq. (11), which derives the average sensing cycle time T_{sense} , includes the distance between fixed nodes, i.e., $|\mathbf{L}_i - \mathbf{L}_j|$. Thus, we can see that T_{sense} becomes smaller by reducing the value $|\mathbf{L}_i - \mathbf{L}_j|$. This idea corresponds to Guideline 2. In addition, from Eq. (14), we can see that the distance of the route from each fixed node should be small in order to improve the efficiency of data transmission processes. This idea corresponds to Guideline 3. Although this guideline is intuitive, it derives the specific value l_{max} as the upper limit of the distance between fixed nodes in order for the network to work. Thus, the strategy adopts this value for determining the locations of fixed nodes. This value is an important parameter that can be derived only from the analysis.

On the other hand, other guidelines, i.e., Guidelines 1 and 4, cannot be intuitively derived because they do not follow the above discussion. For example, we derive Guideline 1 (*The distance between fixed nodes on each communication route and the territory size of each fixed node should be uniform*) by the partial differentiation shown in Eq. (12). This guideline indicates that the performance cannot be improved only by reducing the distances between fixed nodes, and that the moving distance in a territory should not be too large. In addition, Guideline 4 also cannot be intuitively derived because this is derived to avoid the violation of Guideline 1 due to (intuitive) Guidelines 2 and 3.

4.3 Strategy for Deploying Fixed Nodes

Based on the above guidelines, we devise the following strategy for deploying fixed nodes. Note that we design the strategy assuming the rectangular region with the sink node deployed at a corner of the region. Designing the strategy that can be applied to other environments is our future work. Let us use an example where 6 fixed nodes (including the sink node) and 40 mobile nodes are deployed in $2,100 \text{ [m]} \times 2,100 \text{ [m]}$ flatland, and the communication range is 100 [m]

for explaining the strategy.

The strategy for deploying fixed nodes in DATFM/DF is divided into two steps, determining the pattern of deployment, and adjusting the distance between all pairs of fixed nodes in the determined pattern.

4.3.1 Determining Pattern of Deployment

First, DATFM/DF determines the pattern of deployment based on Guidelines 1 and 2. Here, Guideline 2 only considers the moving distance between neighboring territories in a sensing cycle. On the other hand, Guideline 1 considers not only the moving distance between territories but also that in each territory and the efficiency of data transmission processes. Therefore, if we apply Guideline 2 prior to Guideline 1, the performance of operations that Guideline 1 considers may deteriorate. Thus, DATFM/DF first derives multiple candidates of deployment patterns considering Guideline 1 and selects one considering Guideline 2.

- (1) Draw the line from the sink node to the farthest point. Let us define the length of the line as L . Next, calculate the ideal length of the communication route l by the following equations:

$$\begin{aligned} \frac{S_{region}}{N_{fix}} &= \pi \cdot \left(\frac{l}{2}\right)^2 \\ l &= 2 \cdot \sqrt{\frac{S_{region}}{\pi \cdot N_{fix}}}. \end{aligned} \quad (19)$$

In the above equations, we assume the shape of each territory as a circle for simplicity. This equation indicates that all regions have the same size (S_{region}/N_{fix}) (from Guideline 1). Next, calculate the required number of fixed nodes in order to deploy a fixed node at the farthest point from the sink node when the distance between fixed nodes is set as l (as shown in **Fig. 6**). We define this value as N_{hop} . In the example, L becomes $2,970 \text{ [m]}$ ($= 2,100 \cdot \sqrt{2}$) and l becomes 970 [m] ($= 2 \cdot \sqrt{(2,100^2/\pi \cdot 6)}$). Thus, $N_{hop} \approx 3$ ($2,970/970$).

- (2) Divide the region into $N_{hop} + 1$ zones as shown in **Fig. 7**. Then, calculate the number of fixed node deployed in zone i (N_{zone_i}) according to the following equation:

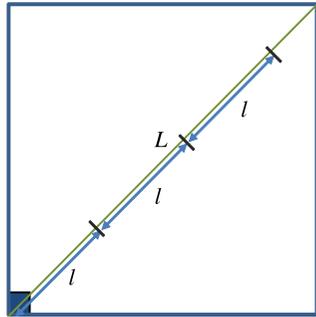


Fig. 6 Calculate N_{hop} .

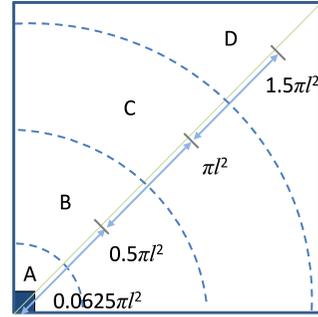


Fig. 7 Divide the region.

$$N_{zone_i} = \left\lceil N_{fix} \cdot \frac{|Z_i|}{S_{region}} \right\rceil. \quad (20)$$

$|Z_i|$ is the size of zone i . In the example, the region is divided into four zones, Z_A , Z_B , Z_C and Z_D whose sizes are respectively $0.0625\pi l^2$, $0.5\pi l^2$, πl^2 , and $1.5\pi l^2$. Since the number of fixed nodes is 6, the number of fixed nodes deployed in each zone respectively becomes 1 ($= \lceil 6 \cdot 0.0625/3.0625 \rceil$), 1 ($= \lceil 6 \cdot 0.5/3.0625 \rceil$), 2 ($= \lceil 6 \cdot 1/3.0625 \rceil$) and 3 ($= \lceil 6 \cdot 1.5/3.0625 \rceil$).

- (3) Make all patterns of deployment that satisfy the following conditions:
 - The distance between adjacent fixed nodes is uniform.
 - The required number of the routes for each fixed node to transfer its holding data to the sink node (we define this value as the *hop-count*) is equal to or more than N_{hop} .
 - The number of fixed nodes in each zone i is equal to or less than N_{zone_i} calculated in the previous step.

Figure 8 shows the patterns of deployment that satisfy the above conditions in the example. In this figure, the distance between adjacent fixed nodes is expressed as K .

- (4) Calculate the total length of moving paths of mobile nodes between all pairs of fixed nodes. For example in Fig. 8 (a), the lengths of the moving paths between all pairs of fixed nodes become as shown in Table 2. Thus, the total length in this pattern becomes $50K$. After that, select the pattern with the minimum length as the initial deployment pattern (from Guideline 2).

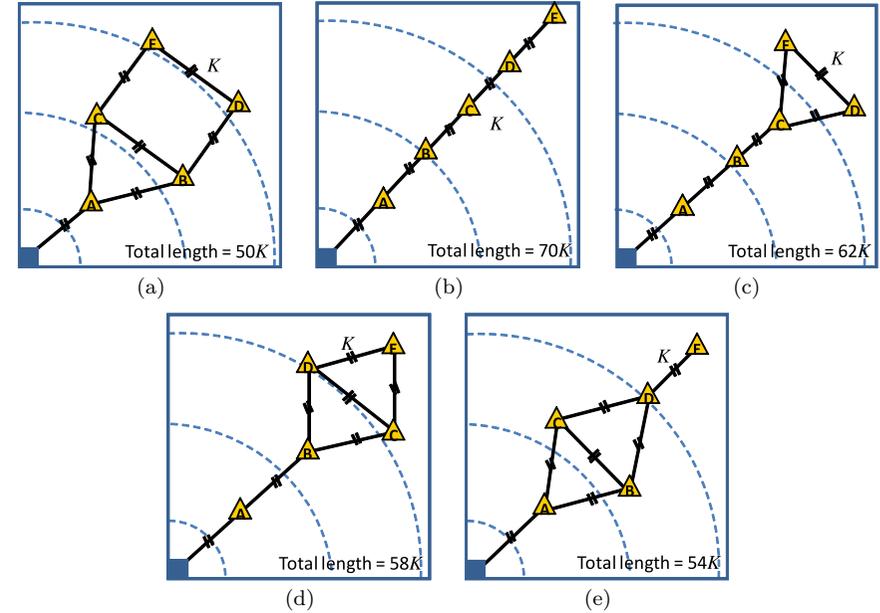


Fig. 8 Deployment patterns.

Table 2 Lengths of moving paths in Fig. 8 (a).

from\to	Sink	A	B	C	D	E
Sink	-	$K(\text{Sink} \rightarrow A)$	$2K(\text{Sink} \rightarrow A \rightarrow B)$	$2K(\text{Sink} \rightarrow A \rightarrow C)$	$3K(\text{Sink} \rightarrow A \rightarrow B \rightarrow D)$	$3K(\text{Sink} \rightarrow A \rightarrow C \rightarrow E)$
A	$K(A \rightarrow \text{Sink})$	-	$K(A \rightarrow B)$	$K(A \rightarrow C)$	$2K(A \rightarrow B \rightarrow D)$	$2K(A \rightarrow C \rightarrow E)$
B	$2K(B \rightarrow A \rightarrow \text{Sink})$	$K(B \rightarrow A)$	-	$K(B \rightarrow C)$	$K(B \rightarrow D)$	$2K(B \rightarrow D \rightarrow E)$
C	$2K(C \rightarrow A \rightarrow \text{Sink})$	$K(C \rightarrow A)$	$K(C \rightarrow B)$	-	$2K(C \rightarrow B \rightarrow D)$	$K(C \rightarrow E)$
D	$3K(D \rightarrow B \rightarrow A \rightarrow \text{sink})$	$2K(D \rightarrow B \rightarrow A)$	$K(D \rightarrow B)$	$2K(D \rightarrow B \rightarrow C)$	-	$K(D \rightarrow E)$
E	$3K(E \rightarrow C \rightarrow A \rightarrow \text{sink})$	$2K(E \rightarrow C \rightarrow A)$	$2K(E \rightarrow C \rightarrow B)$	$K(E \rightarrow C)$	$K(E \rightarrow D)$	-

In the example, Fig. 8 (a) is adopted as the initial pattern.

4.3.2 Adjusting Distance between Fixed Nodes

Next, DATFM/DF adjusts the distance between all pairs of fixed nodes in the

determined pattern.

- (5) Derive the optimal distance between adjacent fixed nodes in order to deploy some fixed nodes far from the sink node (from Guideline 4). First, fixed nodes with the maximum hop-count are deployed at the farthest points from the sink node. Thus, we adjust the distance between adjacent fixed nodes according to the maximum hop-count. Specifically, when the distance between adjacent fixed nodes and the maximum hop-count are respectively defined as l_{opt} and H_{max} , the distance between the sink node and fixed nodes with the maximum hop-count becomes $H_{max} \cdot l_{opt}$. Here, when this value is too large, some fixed nodes may located outside of the target region. To avoid such a situation, we introduce the distance between the sink node and the nearest corner of the region (L_{min}). Specifically, we set l_{opt} in order for the territory of a fixed node with the maximum hop-count to be located within the range of L_{min} from the sink node (see **Fig. 9**). When we assume for the sake of simplicity that the location of a fixed node is the center of the corresponding territory and that the shape of each territory becomes a circle for simplicity, the distance between a fixed node and the boundary of its territory becomes $2/l_{opt}$. Based on this discussion, l_{opt} is calculated by the following equation:

$$l_{opt} = 2 \cdot \frac{L_{min}}{(2 \cdot H_{max} + 1)} \tag{21}$$

In the example, since H_{max} is 3 and L_{min} is 2,100, l_{opt} becomes 600 [m] ($= 2 \cdot 2,100 / (2 \cdot 3 + 1)$).

- (6) Derive the maximum distance between adjacent fixed nodes as l_{max} according to the following equation (from Guideline 3):

$$l_{max} = N_{max} \cdot r_{com} \tag{22}$$

Next, compare l_{max} with l_{opt} and adopt the smaller one as distance between adjacent fixed nodes l_{eff} . In the example, when Th/D is 30, l_{max} becomes 2,000 [m] ($= ((40 + \sqrt{1,600 + 24,000}) / 10) \cdot 100$: see Eq. (18)). Thus, l_{eff} becomes l_{opt} , which is smaller than l_{max} .

- (7) Finally, adjust the locations of fixed nodes. Specifically, adjust the distance between adjacent fixed nodes to l_{eff} while keeping the shape of deployment pattern selected in step (4). In the example, since l_{eff} is 600 [m] (calculated

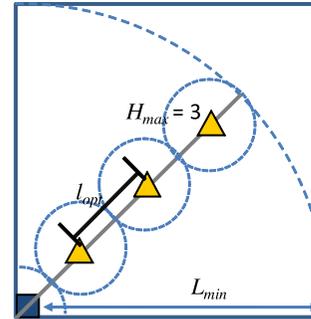


Fig. 9 Adjust the distance.

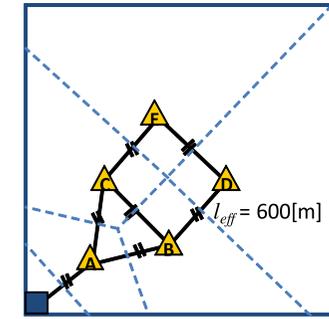


Fig. 10 Deployment of fixed node.

in step (5)), the deployment becomes as shown in **Fig. 10**.

As described in Section 4.2, when the condition of Guideline 3 is not satisfied, the network does not work. On the other hand, Guideline 4 is derived for preventing the violation of Guideline 1 due to Guidelines 2 and 3. Thus, the importance of Guideline 4 becomes lower compared with Guideline 3. In the above strategy, l_{max} and l_{opt} are calculated respectively based on Guidelines 3 and 4. According to Guideline 3, the distance between fixed nodes should be smaller than l_{max} in order for the network to work. On the other hand, according to Guideline 4, the distance should be at least l_{opt} in order to avoid violating Guideline 1. Thus, the strategy adopts the smaller one among l_{max} and l_{opt} as the distance between adjacent fixed nodes l_{eff} in order for l_{eff} not to be larger than l_{max} .

4.4 Discussions

In order to verify the validity of the guidelines, we conducted the simulation experiments. In the experiments, we verify the validities of l_{max} and l_{opt} , which are respectively derived from Guidelines 3 and 4. The simulation environment is basically the same as that in Section 5. There are 5 fixed nodes which are deployed according to the deployment pattern determined in the former part of the strategy in Section 4.3. In this environment, we change the distance between adjacent fixed nodes (K in Fig. 8) and evaluate the throughput, which is defined as the amount of data that arrive at the sink node per 1 [sec]. **Figure 11** shows the simulation result. From this result, the throughput becomes highest when the distance between fixed nodes equals l_{opt} ($= l_{eff}$ in the strategy). Moreover, when

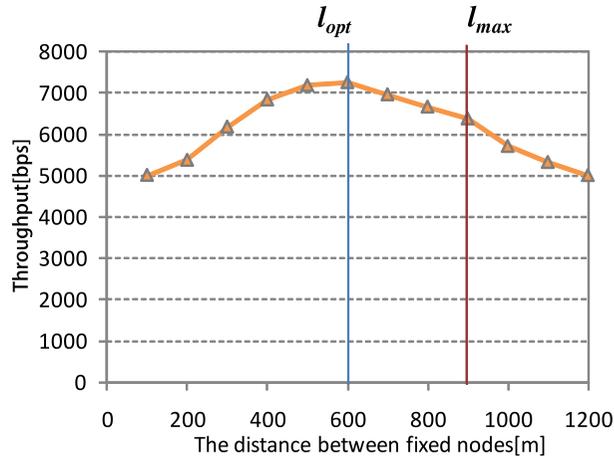


Fig. 11 The effects of the distance between fixed nodes.

the distance is larger than l_{\max} , the throughput begins to decrease drastically. This result indicates that the guidelines derived from the result of the analysis appropriately work in determining the deployment of fixed nodes.

5. Performance Evaluation

In this section, we show results of simulation experiments regarding performance evaluation of DATFM/DF. In the simulation experiments, we compare the performance of DATFM/DF with those of methods described in Section 5.2.

5.1 Simulation Environment

We assume a planetary exploration application in which each sensor acquires the picture, information of minerals or the temperature in the region. Sensor nodes are deployed in a $2,100 [m] \times 2,100 [m]$ flatland. Each sensor node performs sensing at a rate of $100 [\text{bit}/\text{sec} \cdot \text{m}^2]$ and T_{acq} is $30 [\text{sec}]$. The wireless communication range of all nodes and the channel bandwidth are $100 [m]$ and $11 [\text{Mbps}]$, respectively.

There are N_{fix} fixed nodes and N_{mov} mobile nodes. Each mobile node moves with velocity of $5 [m/s]$ in *SM* and $10 [m/s]$ in *TM* and *CM*. Each fixed and mobile node has a memory space whose size is $2,000 [\text{Mbit}]$ and $10 [\text{Mbit}]$, re-

spectively. Each fixed node starts data transmission when the amount of the accumulated data exceeds $1,000 [\text{Mbit}]$. Each fixed node performs sensing every $1,500 [\text{sec}]$.

In this environment, we evaluate the following three criteria during 1 [week]:

- Throughput
The amount of data that arrives at the sink node per 1 [sec].
- Average moving distance
The average of moving distances of all mobile nodes during the simulation period.
- Average delay
The average of the elapsed time after data are acquired until the data arrive at the sink node.

5.2 Comparative Methods

We evaluated the performances of DATFM in all the patterns of deployment of fixed nodes on the grid whose interval is $350 [m]$, and derived the average of each metric. We define the result as *AverageDATFM*. In addition, we adopted the pattern that shows the largest throughput as the *Semi-optimal* deployment.

5.3 Effects of the Number of Fixed Nodes

Figure 12 shows the simulation results when setting the number of mobile nodes as 40 and changing the total number of fixed nodes. The vertical axis indicates throughput in Fig. 12 (a), average moving distance in Fig. 12 (b), and average delay in Fig. 12 (c).

Figure 12 (a) shows that the throughput in DATFM/DF is always larger than that in the average DATFM, and almost same as (sometimes larger than) that in semi-optimal deployment. This indicates that the strategy in DATFM/DF is effective in improving the effectiveness of acquisition and data transmission. Throughputs in all methods increase as the number of fixed nodes increases. This is because the increase in fixed nodes makes the average distance between fixed nodes smaller, and thus, it becomes easier for each mobile nodes to connect to fixed nodes.

Figure 12 (b) shows that the moving distance in DATFM/DF is always smaller than those in semi-optimal deployment and average DATFM. This is because the strategy in DATFM/DF aims to reduce the average distance between fixed

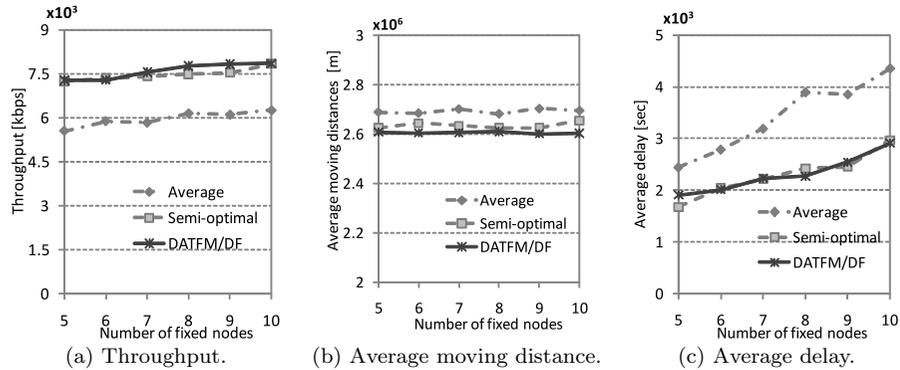


Fig. 12 Effects of number of fixed nodes.

nodes.

Figure 12 (c) shows that the delay in DATFM/DF is always smaller than that in average DATFM. This result shows that the strategy in DATFM/DF improves the effectiveness of data accumulation and transmission. Moreover, delays in all methods become larger as the number of fixed nodes increases. This is because the larger number of fixed nodes, the lower the frequency for each fixed node to connect with mobile nodes. As a result, the time for accumulating data increases in each fixed node.

5.4 Effects of Number of Mobile Nodes

Figure 13 shows the simulation results when setting the number of fixed nodes as 7 and changing the number of mobile nodes. The vertical axis indicates throughput in Fig. 13 (a), average moving distance in Fig. 13 (b), and average delay in Fig. 13 (c).

Figure 13 (a) shows that the throughput in DATFM/DF is always larger than that in average DATFM. This is due to the same reasons as those in Fig. 12 (a). Moreover, throughputs in all methods increase as the number of sensor nodes increase. This is because it becomes easier for each fixed node to collect a sufficient number of mobile nodes to construct a communication route.

Figure 13 (b) shows that the moving distance in DATFM/DF is always smaller than that in average DATFM. This is due to the same reasons as those in Fig. 12 (b). The moving distance in DATFM/DF is smaller than that in semi-

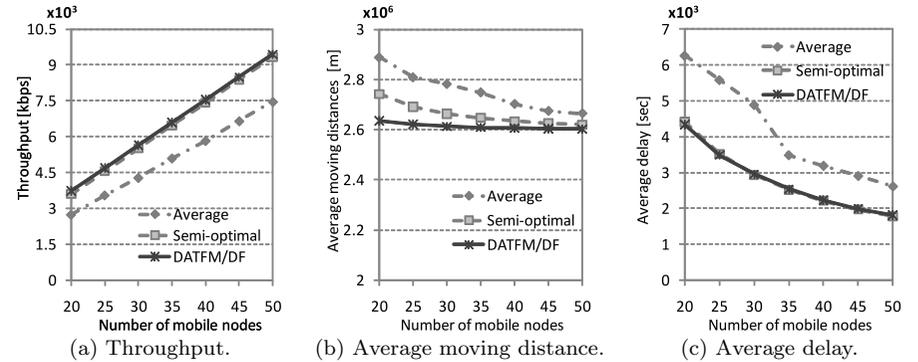


Fig. 13 Effects of number of mobile nodes.

optimal deployment when the number of mobile nodes is small. This is because, DATFM/DF deployed fixed nodes nearby the center of corresponding territories which reduce the moving distance from fixed node to the sensing point. Moreover, the moving distances in all patterns decrease as the number of sensor nodes gets larger. This is because it becomes easier for each fixed node to construct a communication route.

Figure 13 (c) shows that the delay in DATFM/DF is always smaller than that in average DATFM. This is due to the same reasons as those in Fig. 12 (c). Moreover, delays in all methods decrease as the number of sensor nodes gets larger. This is because the times elapsed for accumulating data in each fixed node (T_{acc_i}) decreases.

5.5 Discussion

From the results of the simulation experiments, we can see that DATFM/DF deploys fixed nodes to appropriate locations to achieve high throughput. However, the deployment in DATFM/DF is not optimal since the strategy is designed by the guidelines considering only the sensing rates. However, it is very difficult to find the optimal deployment to maximize the sensing rates. Therefore, we have compared the performance with that in semi-optimal deployment.

Here, to derive the semi-optimal deployment with 7 fixed nodes, we have evaluated throughputs in more than 3,000,000 patterns. When the numbers of fixed nodes and mobile nodes become larger, the number of trials becomes much larger.

On the other hand, DATFM/DF can derive a deployment which achieves good performance without such trials. In addition, DATFM/DF is available in an environment where the number of nodes dynamically changes.

6. Conclusion

In this paper, we have proposed an effective mobile sensor control method DATFM/DF to further improve the effectiveness of data acquisition and transmission of our previous method, DATFM. DATFM/DF strategically deploys fixed nodes based on the analysis of the sensing rate. We have also conducted the simulation experiments to evaluate the performance of DATFM/DF. The results show that DATFM/DF improves performance compared with DATFM.

Since mobile nodes cannot sense their target locations when they are transferring data accumulated by a fixed node, the amount of acquired data tends to decrease in a particular region where data transmissions frequently occur. Moreover, since mobile nodes in DATFM randomly select the territory to perform sensing, the moving distance of mobile nodes increases especially when the distance between fixed nodes is large. Thus, as part of our future work, we plan to investigate and modify the policy for selecting the sensing point of mobile node, in order to achieve highly effective of the data acquisition and transmission.

Moreover, in order to adapt to a harsh environment, we also plan to extend our method to handle node failures. Furthermore, we plan to examine the effects of difference in memory spaces between mobile and fixed nodes. Finally, we plan to implement our proposed method on real sensor nodes and verify its effectiveness on a practical platform.

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References

- 1) Akyildiz, I.F., Pompili, D., and Melodia, T.: Underwater acoustic sensor networks: Research challenges, *Ad Hoc Networks*, Vol.3, No.3, pp.257–279 (2005).
- 2) Cui, J.H., Kong, J., Gerla, M. and Zhou, S.: The challenges of building mobile underwater wireless networks for aquatic applications, *IEEE Network*, Vol.20, No.3, pp.12–18 (2006).
- 3) Treeprapin, K., Kanzaki, A., Hara, T. and Nishio, S.: An effective mobile sensor control method for sparse sensor networks, *Sensors*, Vol.9, No.1, pp.327–354 (2009).
- 4) Ad Hoc Committee on the Solar System Radiation Environment and NASA's Vision for Space Exploration: A Workshop, National Research Council: Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop (2006).
- 5) Rao, R. and Kesidis, G.: Purposeful mobility for relaying and surveillance in mobile ad hoc sensor networks, *IEEE Trans. Mobile Computing*, Vol.3, No.3, pp.225–232 (2004).
- 6) Shinjo, T., Kitajima, S., Ogawa, T., Hara, T. and Nishio, S.: Mobile sensor control methods for reducing power consumption in sparse sensor network, *Proc. Int'l Workshop on Sensor Network Technologies for Information Explotion Era (SeNTIE 2008)*, pp.133–140 (2008).
- 7) Son, D., Helmy, A. and Krishnatchari, B.: The effect of mobility-induced location errors on geographic routing in mobile ad hoc and sensor networks: Analysis and improvement using mobility prediction, *IEEE Trans. Mobile Computing*, Vol.3, No.3, pp.233–245 (2004).
- 8) Suzuki, R., Makimura, K., Saito, H. and Tobe, Y.: Prototype of a sensor network with moving nodes, *Proc. Int'l Workshop on Networked Sensing Systems (INSS 2004)* (2004).
- 9) Tobe, Y. and Suzuki, T.: WISER: Cooperative sensing using mobile robots, *Proc. Int'l Conf. on Parallel and Distributed Systems (ICPADS 2005)*, pp.388–392 (2005).
- 10) Wang, K. and Ramanathan, P.: Collaborative sensing using sensors of uncoordinated mobility, *Proc. Int'l Conf. on Distributed Computing in Sensor Systems (DCOSS 2005)*, pp.293–306 (2005).
- 11) Wang, Y. and Wu, H.: Delay/fault-tolerant mobile sensor network (DFT-MSN): A new paradigm for pervasive information gathering, *IEEE Trans. Mobile Computing*, Vol.6, No.9, pp.1021–1034 (2007).
- 12) Wang, Y. and Wu, H.: DFT-MSN: The delay fault tolerant mobile sensor network for pervasive information gathering, *Proc. IEEE Infocom 2006* (2006).
- 13) Arboleada, C.L.M. and Nasser, N.: Cluster-based routing protocol for mobile sensor networks, *Proc. Int'l Conf. on Quality of Service in Heterogeneous Wired/Wireless Networks (QShine 2006)* (2006).
- 14) Yuan, Q., Cardei, I. and Wu, J.: Predict and relay: An efficient routing in disruption-tolerant networks, *Proc. MobiHoc 2009*, pp.95–104 (2009).
- 15) Liu, C. and Wu, J.: Scalable routing in delay tolerant networks, *Proc. MobiHoc 2007*, pp.51–60 (2007).
- 16) Vasilescu, I., Kotay, K., Rus, D., Dunbabin, M. and Corke, P.I.: Data collection, storage, and retrieval with an underwater sensor network, *Proc. SenSys 2005*, pp.154–165 (2005).
- 17) Hull, B., Bychkovsky, B., Zhang, Y., Chen, K., Goraczko, M., Miu, A., Shih, E., Balakrishnan, H. and Madden, S.: CarTel: A distributed mobile sensor computing

system, *Proc. SenSys 2006*, pp.125–138 (2006).

- 18) Hu, L. and Evans, D.: Localization for mobile sensor networks, *Proc. ACM Mobicom 2004*, pp.45–57 (2004).
- 19) Pompili, D., Melodia, T. and Akyildiz, L.F.: Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks, *Proc. ACM Mobicom 2006*, pp.298–309 (2006).

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