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Effective Node Deployment in Sparse Mobile Sensor Networks

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Abstract: In this paper, we propose DATFM/DA (Data Acquisition and Transmission with Fixed and Mobile node with Deployment Adjusting), which is an extension of our previous mobile sensor control method, DATFM. DATFM/DA uses two types of sensor nodes, *fixed node* and *mobile node*. The data acquired by the nodes are accumulated on a fixed node before being transferred to the sink node. DATFM/DA divides the target region into multiple areas, and statically deploys mobile nodes to each divided area. In addition, DATFM/DA adjusts the number of mobile nodes deployed in each area based on the analysis of the performance. We also conduct simulation experiments to verify that this method further improves the performances of sensing and data transfer.

Keywords: sensor network, mobile sensor, node deployment, analysis

1. Introduction

Recent advance in wireless communication technology has led to an increasing interest in wireless sensor networks. Due to the ability to construct a large-scale sensing system by cooperative behaviors of multiple sensor nodes, wireless sensor networks are expected to be applied to many applications such as environmental monitoring, investigation of ecological system 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 [1], [10]. In such environments, the deployment of sensor nodes becomes too sparse to achieve sufficient sensing and data transfer. For example, in a 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 an enough 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 a deployment becomes impossible in a building or under the heap of ruins. Furthermore, long range radio waves cannot improve the connectivity in these applications. For example, in a building or under the heap of ruins, long range radio waves are much affected by the ambient surroundings such as walls and rubbles. In addition, as pointed out in Ref. [2], in planetary exploration, there is a variety of terrains such as craters, canyons and volcanoes that significantly affect long-range wireless communications. Moreover, long-range wireless radio waves tend to be much affected by the radiation in such environments. Therefore, long range communications become unstable, and thus, data transfers fail frequently.

To solve this problem, 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 sensor networks which fully or partially include mobile sensors as *mobile sensor networks*.

Mobile sensor networks are expected to be applied to a wide variety of applications. Among them, one of the typical applications is monitoring a target region. In this kind of application, the system has to acquire data from the whole region. For example, in an investigation of the ocean floor, in order to obtain the map of the landscape or the temperature, or to detect a sunken ship or mineral vein, the whole region has to be monitored.

Considering these applications, we proposed DATFM (Data Acquisition and Transmission with Fixed and Mobile node) [14], which is a mobile sensor control method for acquiring data from the whole region in sparse sensor networks. DATFM uses two types of sensor nodes, *fixed node* and *mobile node*. A fixed node has two roles, temporarily accumulating data acquired by mobile nodes and constructing a communication route between fixed nodes for transmitting the accumulated data toward the sink node. By using the fixed nodes, DATFM can effectively control the behaviors of mobile nodes to perform sensing and data transfer in a sparse network.

Here, DATFM is a fundamental method that controls mobile sensors in order to efficiently gather sensor data from the whole region. Thus, mobile nodes in this method move around the

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whole region. This increases the moving distance of mobile nodes, and degrades the performances of sensing and data transfer. In this paper, in order to alleviate the increase of the moving distance of mobile nodes, we propose DATFM/DA (DATFM with Deployment Adjusting) as an extension of DATFM. DATFM/DA divides the target region into multiple areas and statically deploys mobile nodes to each area. Each mobile node performs sensing operations only in the area where it is deployed. By doing so, the moving distance of each mobile node can be reduced. In addition, DATFM/DA determines the number of mobile nodes deployed to each area in order to monitor the whole target region efficiently.

The remainder of this paper is organized as follows. In Section 2, we briefly present the system model assumed in this paper and the conventional data transfer methods in mobile sensor networks. In Section 3, we explain our previous method, DATFM. In Section 4, we present DATFM/DA, which is proposed in this paper. The results of simulation experiments are presented in Section 5. 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 and hazardous square region with a small number of nodes. To acquire data from the whole region with a small number of nodes, mobile sensors are introduced into the network. Following the conventional works [7], [8], [9], [16], we assume that each mobile sensor can move freely and autonomously. Each mobile sensor acquires data whose sizes are relatively large such as pictures or movies. Moreover, we assume that the cost of preparing storage media is very large. This is because, it is well known that high-density storage media tend to be easily broken due to several effects such as radiation in hazardous environments [4]. Thus, in order for a sensor node to equip with large storage media, it is necessary to protect the storage by using materials or devices which can alleviate hazardous effects such as radiation.

Each mobile sensor knows its present location by using GPS or other location detection methods [3], [5]. The sensor data acquired by mobile sensors are transfered to the sink node located at a corner of the area similar to the assumption in many conventional works such as target detecting, tracking and environment monitoring [6], [10], [17]. Each mobile sensor has a unique identifier in the network. In addition, we assume that all mobile sensors have the same sensor and radio devices. Thus, the sensing and wireless communication ranges are same among all mobile sensors. Following the conventional works [11], [12], [13], [17], for simplicity, we assume that there are no obstacles in the region.

2.2 Related Work

Until now, many studies on controlling the mobility of mobile sensors for sensing and data transfer have been conducted.

In Ref. [18], Wang et al. proposed a data transfer method that introduces some special nodes which are equipped with long-range radio transmitter. In Ref. [11], Shinjo et al. proposed another data transfer method which introduces a broadcast system. 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 environment assumed in this paper.

On the other hand, several data transfer methods without any special equipment have been proposed [13], [17]. In Ref. [13], Tobe et al. proposed RAMOS (Routing Assisted by Moving Objects) which is a data transfer method with mobile sensors. RAMOS defines several modes (classified into three categories listed below) for each sensor. Each sensor autonomously controls its behavior by changing its mode according to the existence of data.

[Category1] Fixed: A sensor does a sensing operation without moving. If a neighboring sensor which is within the communication range is located closer to the sink node, the sensor transmits the data to the neighboring sensor.

[Category2] Moving: A sensor does a sensing operation and transfers the data by moving to the sink node.

[Category3] Transmitting: A sensor moves around the area to find other sensors that hold data. When it connects to such a sensor, it receives and transfers the data by moving to the sink node.

In RAMOS, each sensor transfers acquired data to the sink node by changing its mode autonomously.

In Ref. [17], Wang et al. proposed methods using uncoordinated mobile nodes (UM nodes). In this method, each UM node acquires data until the amount of the acquired data reaches the memory capacity. In addition, this method proposes two mobility models of UM nodes, the multi-homed random way point model (*UM-random*) and the controlled mobile nodes model (*UM-controlled*). In UM-random, each UM node randomly chooses the destination and moves there. After reaching the destination, it stochastically determines whether it returns to the sink node or it moves to a new destination. On the other hand, in UM-controlled, the moving path of each UM node is determined in advance and each node does the sensing operation while moving along its path.

In these methods, since each mobile sensor has to move to the sink node to transfer acquired data in most cases, the moving cost increases much. Moreover, in a sparse network, since each sensor has few opportunities to connect to other sensors, the efficiency of sensing and data transfer becomes low.

3. DATFM: Our Previous Method

In this section, we present our previous method, DATFM (Data Acquisition and Transmission with Fixed and Mobile node) [14]. As described in Section 1, DATFM introduces fixed nodes. The data acquired by nodes are accumulated on a fixed node before being transferred to the sink node. In addition, the accumulated data are transferred to the sink node by constructing communication routes between fixed nodes.

3.1 Definitions of Nodes

Before we move to the details of DATFM, here we present the detailed functions of fixed and mobile nodes.

3.1.1 Fixed Node

A fixed node does not move. It has a 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. Here, the sink node is classified

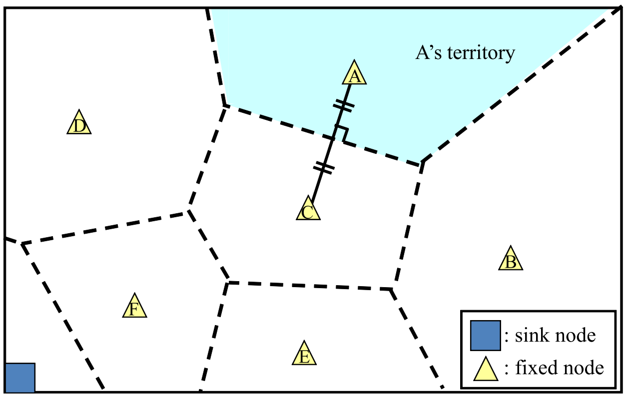


Fig. 1 Dividing the region.

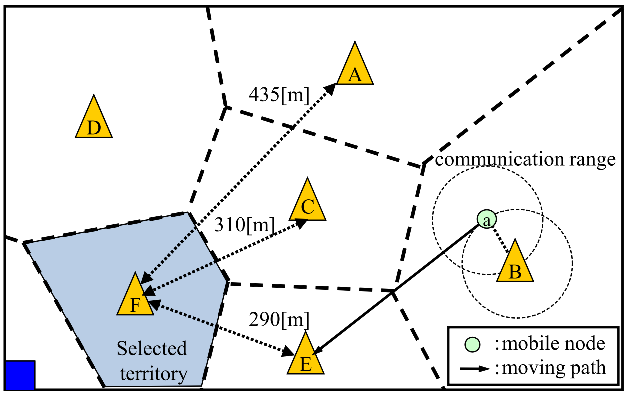


Fig. 2 Moving path of a mobile node.

as a fixed node in DATFM. The locations of all fixed nodes are known by all nodes. As described in Section 2.1, the cost of preparing the storage media is very large. Thus, considering the cost constraint, we deploy a small number of fixed nodes, which have large storage devices.

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 ones. 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 its *territory*. **Figure 1** shows an example of a Voronoi diagram and divided territories. Furthermore, each fixed node determines the sensing points of mobile nodes to perform sensing operations in its territory. In this paper, we assume that a fixed node controls the sensing point of each mobile node in order for the entirety of its territory to be monitored uniformly.

3.1.2 Mobile Node

A mobile node moves around the region. In addition, it has the following three 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 a new territory to move.

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 Sensing Operations 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, which can be derived using the locations of fixed nodes. By doing so, DATFM aims to monitor the whole region. After that, it moves to the territory by the following steps:

(1) The mobile node moves to connect to 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 territory that the mobile nodes currently exists. After that, it moves to the fixed node that is the nearest to the fixed node in the selected territory. **Figure 2** shows an example in which mobile node *a* chooses the next fixed node to move. After transmitting its acquired data to fixed node *B*, mobile node *a* calculates the distances between fixed node *F* that has charge of the selected territory and fixed nodes *A*, *C*, and *D*, which are adjacent to the current (*B*'s) territory. After that, it chooses fixed node *E* 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 connected fixed node. Then it moves there and performs the sensing operation.

This moving strategy enables each fixed node to have many opportunities to connect with mobile nodes. Therefore, this strategy makes it easy for fixed nodes to collect mobile nodes in the data transmission process.

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, Th.

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). Next, the source node sends a *RReq* to a mobile node that firstly 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 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 *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

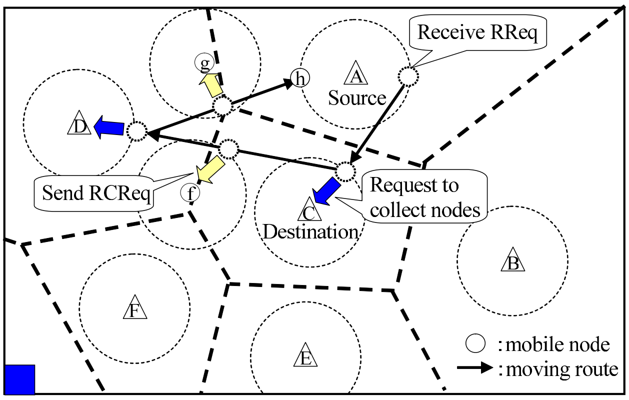


Fig. 3 Collecting mobile nodes.

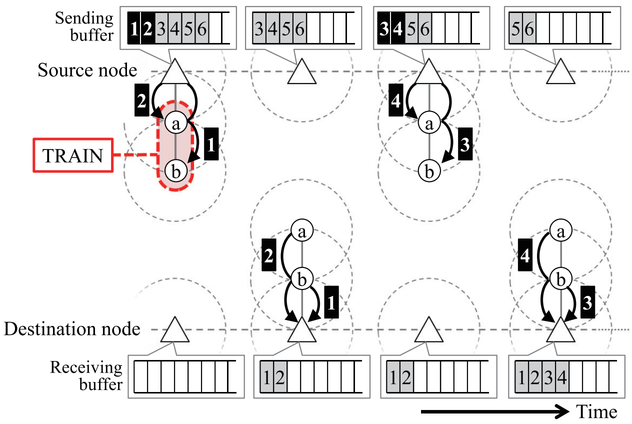


Fig. 4 Train transmission.

node *A*, 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 firstly connects to a mobile node in *TM*. Here, when the number of collected mobile nodes is smaller than the required number of mobile nodes to construct 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 transfered by the movement and communication of the formed train as shown in **Fig. 4**. When another mobile node in *TM* connects to the source node, the source node adds the connected node to the train until the completed communication route is constructed.

4. DATFM/DA

In this section, we propose an extended method of DATFM, named DATFM/DA (DATFM with Deployment Adjusting) in order to alleviate the increase of moving distance of mobile nodes.

4.1 Design

As described in Section 3.2, each mobile node in DATFM selects a territory to perform sensing according to the probability which is proportional to the size of each territory. By doing so, the whole region can be monitored even when some mobile nodes become unavailable due to the battery exhaustion or physical damages. However, in some environments where mobile nodes with much higher durability are deployed, mobile nodes do not need to move around the whole region, i.e., the movement of mobile nodes in DATFM becomes redundant. Thus, when we can alleviate the redundant movement of mobile nodes, a further improvement in efficiencies of sensing and data transfer is expected. Based on this discussion, DATFM/DA statically assigns a territory for each mobile node in order to alleviate the increase of moving distance. Specifically, each mobile node performs sensing operations only in its assigned territory. Moreover, when a fixed node starts data transmission, it constructs the communication route only using mobile nodes deployed in its territory. Thus, DATFM/DA does not use the collection of mobile nodes by a mobile node in *CM*, described in Section 3.3. By doing so, it is expected that the delay for a data transmission decreases.

Moreover, in order to monitor the whole region uniformly, it is important to determine the appropriate number (ratio) of mobile nodes deployed to each territory. Intuitively, the larger the size of a territory is, the more mobile nodes should be deployed to the territory. However, since some mobile nodes have to stop their sensing operations for transferring data in a data transmission process, the efficiency of sensing deteriorates in a particular territory where data transmissions frequently occur. For example, fixed nodes near the sink node receive data accumulated by other fixed nodes far from the sink node, and thus, frequently perform data transmissions. Therefore, mobile nodes in such ‘busy’ territories have a lower chance to perform sensing operations. Such a skew of the amount of acquired data cannot be allowed in some applications which need to acquire data in the whole region uniformly, or those which specify the required (minimum) amount of acquired data in the entire region. In order to avoid such a skew, DATFM/DA determines the number of mobile nodes deployed to each territory considering not only the size of the territory but also the frequency of data transmissions.

In what follows, we present the details of sensing operations of mobile nodes and the data transmission in DATFM/DA. After that, we explain the strategy to determine the number of mobile nodes deployed to each territory.

4.1.1 Sensing Operations of Mobile Nodes

As described above, DATFM/DA statically assigns a territory for each mobile node. Thus, each mobile node performs sensing operations only in its assigned territory. After performing a sensing operation, a mobile node moves to the fixed node in its assigned territory, receives the information on the next sensing point (in the same territory) from the fixed node, and moves to that point.

4.1.2 Data Transmission in DATFM/DA

Similar to DATFM, a fixed node starts data transmission to its destination node when the amount of the accumulated data in its memory exceeds the threshold. First, the fixed (source) node sends a *RCReq* to a mobile node that firstly connects to itself. The mobile node which receives the *RCReq* immediately changes its

Table 1 Parameters given 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., $S_{\text{region}} = \sum_i |\mathbf{T}_i|$).
v_m	velocity of mobile nodes in *SM*.
v_r	velocity of mobile nodes in *TM*.
T_{acq}	time for a sensing operation.
N_{fix}	number of fixed nodes in the whole region.
N_{mov}	total number of mobile nodes in the whole region.
Th	threshold for starting data transmission.
D	data size acquired in a sensing operation.
r_{com}	communication range of all nodes.

mode into *TM*. Then the source node starts a train transmission using the connected mobile node. When another mobile node connects to the source node, the source node adds the connected node to the train until the complete communication route is constructed.

4.2 Adjusting the Number of Mobile Nodes

As described in Section 4.1, it is desirable to deploy more mobile nodes in a territory where data transmissions frequently occur. By doing so, even when some mobile nodes stop sensing for transferring data in a territory, efficient sensing can be performed by using the remaining mobile nodes.

In order to determine the number of mobile nodes, we analyze the *sensing rate*, R_{sense}, and the *sensing amount*, A_{sense}, in each territory. The sensing rate in a territory is defined as the number of sensing operations performed in a unit of time. The sensing amount is defined as the total amount of data acquired in a unit area in a unit of time. After analyzing these two metrics, we propose a strategy to deploy mobile nodes to each territory.

4.2.1 Assumptions

Before starting the analysis, we show the assumed environment in this section. As described in Section 4.1, in DATFM/DA, each mobile node performs sensing operations only in its assigned territory. We assume that the parameters in **Table 1** are given. We also define the following two cycles:

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

4.2.2 Analysis of R_{sense} and A_{sense}

From the definition of the sensing cycle, R_{sense} is calculated as the inverse of T_{sense}. As an example, we assume a mobile node in Fig. 5 which performs a sensing operation in $\mathbf{T}_B$. First, since the distance between fixed node B and the sensing point is $|\mathbf{d}_B - \mathbf{L}_B|$, the total time elapsed of the sensing cycle becomes

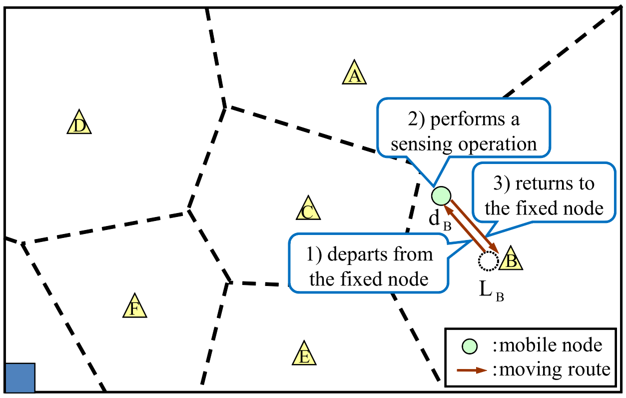


Fig. 5 Operations in a sensing cycle.

$T_{acq} + 2 \cdot |\mathbf{d}_B - \mathbf{L}_B|/v_m$. Here, when the fixed node controls the sensing point in order for the entirety of 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 $\mathbf{T}_B$ (we express this value as $ave(|\mathbf{d}_i - \mathbf{L}_i|)$). Therefore, the average sensing cycle time of a mobile node that performs a sensing operation in $\mathbf{T}_i$, T_{sense_i}, becomes:

$$T_{\text{sense}_i} = T_{\text{acq}} + 2 \cdot \frac{ave(|\mathbf{d}_i - \mathbf{L}_i|)}{v_m}. \quad (1)$$

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

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

N_{free_i} can be represented by using the required number of mobile nodes to construct a communication route (N_{req_i}) and the frequency of data transmission R_{route_i} from fixed node i, that is,

$$N_{\text{free}_i} = N_{\text{mov}_i} - (R_{\text{route}_i} \cdot N_{\text{req}_i}). \quad (2)$$

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

$$R_{\text{sense}_i} = \frac{1}{T_{\text{sense}_i}} \cdot \left(1 - \frac{R_{\text{route}_i} \cdot N_{\text{req}_i}}{N_{\text{mov}_i}}\right). \quad (3)$$

In the above equations, N_{mov_i} is the number of mobile nodes that exist in $\mathbf{T}_i$. N_{req_i} is represented by $|\mathbf{L}_i - \mathbf{L}_d|/r_{\text{com}}$ where $\mathbf{L}_d$ is the location of the destination node of the data transmission. R_{route_i} is the ratio of time elapsed for a data transmission (T_{transmit_i}) to the average transfer cycle time (T_{transfer_i}), that is, $T_{\text{transmit}_i}/T_{\text{transfer}_i}$. 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 receives data from mobile nodes, 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 the average sensing cycle time and the inverse of N_{mov_i}. Therefore, T_{acc_i} is represented by the following equation:

$$T_{\mathrm{acc}_i} = \frac{Th}{D} \cdot T_{ave_i} = \frac{Th}{D} \cdot \frac{T_{\mathrm{sense}_i}}{N_{\mathrm{mov}_i}}. \quad (4)$$

T_{transmit_i} is the total time from when fixed node i starts a 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, a train departs from the source node, moves to the destination, transmits data, and returns to the source node. The first round is conducted by a train that consists of one mobile node and the elapsed time for this round ($T_{\mathrm{train}_{i_1}}$) becomes $2 \cdot (|\mathbf{L}_i - \mathbf{L}_j| - 2 \cdot r_{\mathrm{com}})/v_r$. The number of mobile nodes which newly connect to fixed node i during this round ($N_{\mathrm{train}_{i_1}}$) is $T_{\mathrm{train}_{i_1}}/T_{ave_i}$. Thus, in the second round, the train transmission is conducted by $N_{\mathrm{train}_{i_1}} + 1$ mobile nodes. The elapsed time for this round is represented by the following equation:

$$\begin{aligned} T_{\mathrm{train}_{i_2}} &= \frac{2 \cdot \left(|\mathbf{L}_i - \mathbf{L}_j| - r_{\mathrm{com}} \cdot \left(2 + \frac{T_{\mathrm{train}_{i_1}}}{T_{ave_i}}\right)\right)}{v_r} \\ &= K \cdot T_{\mathrm{train}_{i_1}} \qquad \left(K = 1 - \frac{2 \cdot N_{\mathrm{mov}} \cdot r_{\mathrm{com}}}{v_r \cdot T_{\mathrm{sense}_i}}\right). \end{aligned} \quad (5)$$

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

$$\begin{aligned} T_{\mathrm{train}_{i_N}} &= \frac{2 \cdot (|\mathbf{L}_i - \mathbf{L}_j| - r_{\mathrm{com}} \cdot (2 + N_{\mathrm{train}_{N-1}}))}{v_r} \\ &= K^{N-1} \cdot T_{\mathrm{train}_{i_1}}. \end{aligned} \quad (6)$$

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

$$\begin{aligned} T_{\mathrm{transmit}_i} &= T_{\mathrm{train}_{i_1}} + T_{\mathrm{train}_{i_2}} + \cdots + T_{\mathrm{train}_{i_N}} \\ &= T_{\mathrm{train}_{i_1}} + K \cdot T_{\mathrm{train}_{i_1}} + \cdots + K^{N-1} \cdot T_{\mathrm{train}_{i_1}} \\ &= \frac{(1 - K^{N-1}) \cdot T_{\mathrm{train}_{i_1}}}{(1 - K)}. \end{aligned} \quad (7)$$

Since the required time for transferring data between connected nodes is much smaller than that for moving between fixed nodes, we neglect the time elapsed for transferring data after constructing the completed communication route. Thus, we suppose T_{transmit_i} is equal to the time after starting the first round until the complete communication route is constructed. Here, as shown in Eq. (5), K is smaller than 1. In addition, since we assume a sparse network environment, N tends to be large. Thus, we assume that $K^{N-1} \approx 0$ and T_{transmit_i} can be represented by the following equation:

$$T_{\mathrm{transmit}_i} \approx \frac{T_{\mathrm{train}_{i_1}}}{1 - K} = \frac{T_{\mathrm{train}_{i_1}} \cdot v_r \cdot T_{\mathrm{sense}_i}}{2 \cdot r_{\mathrm{com}} \cdot N_{\mathrm{mov}}}. \quad (8)$$

Since the accumulated data are transmitted toward the sink node via nearby fixed nodes, some fixed nodes receive data accumulated by other fixed nodes. Such fixed nodes accumulate data faster than others. Thus, data transmissions frequently occur in the territories of these fixed nodes. To consider such a skew of frequency of data transmissions, let us define the number of fixed nodes which transmit data via fixed node i as N_{data_i}. For example in **Fig. 6**, N_{data_F} becomes 5 because fixed node F receives data accumulated by five fixed nodes $\{A, B, C, D, E\}$. Using N_{data_i}, we adjust the time elapsed for accumulating data (T_{acc_i}) and that

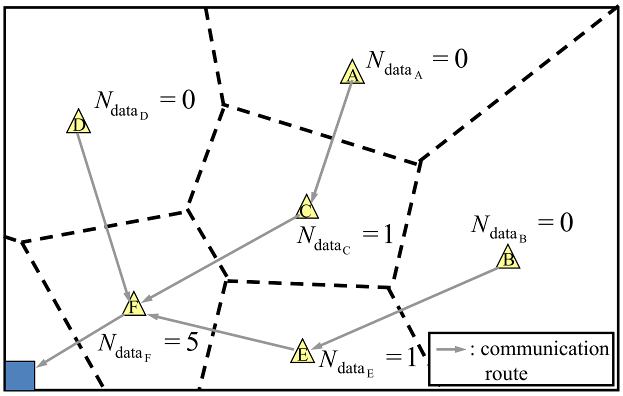


Fig. 6 N_{data} of fixed nodes.

elapsed for data transmission (T_{transmit_i}). Fixed node i receives data accumulated by N_{data_i} fixed nodes in addition to that acquired by mobile nodes in its territory. Thus, we assume that fixed node i accumulates data ($N_{\mathrm{data}_i} + 1$) times faster than other fixed nodes whose N_{data} equals to 0. Thus, we express the time elapsed for accumulating data (T'_{acc_i}) as $T_{\mathrm{acc}_i}/(N_{\mathrm{data}_i} + 1)$. On the other hand, fixed node i transmits data ($N_{\mathrm{data}_i} + 1$) times larger than other fixed nodes whose N_{data} equals to 0. Thus, we express the time elapsed for data transmission (T'_{transmit_i}) as $(N_{\mathrm{data}_i} + 1) \cdot T_{\mathrm{transmit}_i}$. From the above discussion, R_{route_i} is represented by the following equation:

$$\begin{aligned} R_{\mathrm{route}_i} &= \frac{T'_{\mathrm{transmit}_i}}{T'_{\mathrm{transmit}_i} + T'_{\mathrm{acc}_i}} \\ &= \frac{(N_{\mathrm{data}_i} + 1) \cdot T_{\mathrm{transmit}_i}}{((N_{\mathrm{data}_i} + 1) \cdot T_{\mathrm{transmit}_i}) + \frac{T_{\mathrm{acc}_i}}{N_{\mathrm{data}_i} + 1}}. \end{aligned} \quad (9)$$

Finally, the total amount of data acquired in $\mathbf{T}_i$ in a unit of time is derived by $R_{\mathrm{sense}_i} \cdot N_{\mathrm{mov}_i}$. Consequently, the sensing amount in $\mathbf{T}_i$ (A_{sense_i}) is represented by the following equation:

$$\begin{aligned} A_{\mathrm{sense}_i} &= R_{\mathrm{sense}_i} \cdot \frac{N_{\mathrm{mov}_i}}{|\mathbf{T}_i|}. \\ &= \frac{N_{\mathrm{mov}_i}}{|\mathbf{T}_i| \cdot T_{\mathrm{sense}_i}} \cdot \left(1 - \frac{R_{\mathrm{route}_i} \cdot N_{\mathrm{req}_i}}{N_{\mathrm{mov}_i}}\right). \end{aligned} \quad (10)$$

4.2.3 Strategy to Deploy Mobile Nodes

Using the result of the analysis, DATFM/DA deploys mobile nodes to each territory. First, DATFM/DA deploys one mobile node to each territory. After that, DATFM/DA deploys the remaining mobile nodes one by one according to the requirement specified by the application. In this section, we deploy mobile nodes by the following steps assuming an application that monitors the whole region uniformly:

(1) Calculate A_{sense} of each territory by using Eq. (10).
(2) Add one mobile node to the territory with the lowest A_{sense} among all territories.
(3) Repeat step 2 until all mobile nodes are deployed.

By doing so, DATFM/DA can achieve a higher sensing amount even in a territory where data transmissions frequently occur.

5. Performance Evaluation

In this section, we show the results of simulation experiments regarding performance evaluation of DATFM/DA. In the simulation experiments, we assume an application that aims to monitor the whole region uniformly. We compare the performances of DATFM/DA with the following five methods:

- **DATFM**: A mobile sensor control method we have proposed in Ref. [14]. By comparing the performance of this method with those of DATFM/DA and DATFM-area, we verify the effectiveness of the statical territory assignment for each mobile node.
- **RAMOS**: A mobile sensor control method proposed in Ref. [13]. In this method, each mobile node in Category2 randomly selects the next sensing point (territory to perform sensing) from the whole region.
- **DATFM-area**: The number of mobile nodes deployed to each territory is determined only based on the size of territories. Specifically, the number of mobile nodes assigned to $\mathbf{T}_i$ is set as $\lfloor N_{\rm mov} \cdot \mathbf{T}_i / S_{\rm region} \rfloor$. The behavior of each node is the same as that in DATFM/DA. By comparing the performance of this method with that of DATFM/DA, we verify the effectiveness of the adjustment of the number of mobile nodes deployed to each territory.
- **UM-random**: A mobile sensor control method proposed in Ref. [17]. In this method, each UM node randomly chooses the destination and moves there to acquire data.
- **UM-controlled**: A mobile sensor control method proposed in Ref. [17]. In this method, UM nodes move according to the predetermined moving paths.

5.1 Simulation Environment

We assume an application of planetary exploration 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] × 2,100 [m] flatland. Each mobile node performs a sensing operation with the rate of 100 [bit/sec · m^2] and T_{acq} is set as 30 [sec]. The wireless communication range of all nodes and the channel bandwidth are 100 [m] and 11 [Mbps], respectively.

In the experiment, each mobile node moves with a velocity of 5 [m/s] in *SM* and 10 [m/s] in *TM*. In DATFM, each mobile node in *CM* moves with a velocity of 10 [m/s]. Each fixed and mobile node has a memory space whose size is 5,000 [Mbit] and 10 [Mbit], respectively. Each fixed node starts a data transmission when the amount of the accumulated data exceeds 1,000 [Mbit]. Each fixed node performs a sensing operation every 1,500 [sec]. The fixed nodes in DATFM/DA, DATFM-area, are deployed to the same locations of fixed nodes in DATFM.

In RAMOS, there are $N_{\rm fix}$ nodes in Category1, $N_{\rm fix}$ nodes in Category3, and $(N_{\rm mov} - N_{\rm fix})$ nodes in Category2. This parameter setting is to make the total number of nodes in Category3 and Category2 in RAMOS equal to $N_{\rm mov}$ and to guarantee that all nodes in Category 1 can transfer data to the sink node by using nodes in Category2. Nodes in Category1 have a memory space of 1,000 [Mbit]. Nodes in Category3 and Category2 have a memory space of 10 [Mbit]. Nodes in Category3 and Category2 move with a velocity of 5 [m/s] when sensing and gathering data, and 10 [m/s] when transferring data to the sink node.

In UM-random and UM-controlled, there are $(N_{\rm mov} + N_{\rm fix})$ UM nodes. Each UM node has a memory space of 10 [Mbit]. Each node moves with a velocity of 5 [m/s] when sensing, and 10 [m/s] when transferring data.

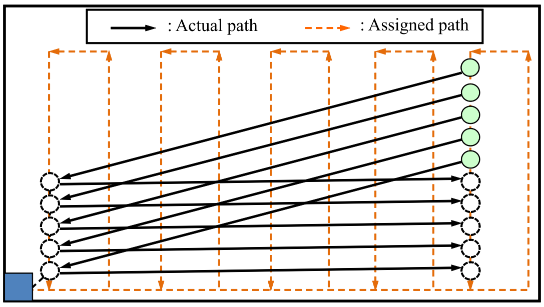


Fig. 7 Moving path in UM-controlled ($N_{\rm mov} + N_{\rm fix} = 5$).

Each UM node starts transferring data to the sink node when the amount of the accumulated data exceeds 10 [Mbit] (i.e., each node transfers data after a sensing operation). In UM-controlled, moving paths of UM nodes are predetermined as shown in **Fig. 7**. In this figure, all UM nodes form a line segment (like a train in DATFM) and move on a fixed path. More specifically, after performing a sensing operation, UM nodes move so that the node at the end of the line segment connects to the sink node, while keeping the shape of the segment. Then, the accumulated data are transferred to the sink node via the multi-hop communication route. Finally, UM nodes move to the next sensing point.

In this environment, we run 100 simulations each of which consists of 1 [week] changing the locations of fixed nodes (or nodes in Category1 in RAMOS).

5.2 Comparison of Throughput

First, we compared the throughput in the region among DATFM/DA, DATFM, RAMOS, DATFM-area, UM-random, and UM-controlled. The throughput is defined as the amount of data that arrive at the sink node per 1 [sec]. In the experiment, we set $N_{\rm fix}$ and $N_{\rm mov}$ as 10 and 40, respectively.

Figure 8 shows the distribution of the throughput in the whole region (The dark blue square shows the sink node). From the results, throughputs in DATFM-area and DATFM/DA become much larger than those in DATFM, RAMOS, UM-random, and UM-controlled. This is due to the reduction of the moving distance of each mobile node for a sensing operation. On the other hand, we can see the skew of the throughput in DATFM/DA and DATFM-area. Especially, the skew of the throughput in DATFM-area seems to be larger than that in DATFM/DA. In order to investigate the skew of the throughput, we evaluated the average, maximum, and minimum throughput among the whole region in each simulation. **Figure 9** shows the results. In these figures, the horizontal axis on all graphs indicates the simulation ID which is sorted by the average throughput in DATFM/DA. The vertical axis indicates the average throughput in Fig. 9 (a), the maximum throughput in Fig. 9 (b), and the minimum throughput in Fig. 9 (c). From these results, we can see that DATFM/DA always achieves a larger minimum throughput than that in DATFM-area although the maximum throughput in DATFM-area is larger than (sometimes same as) that in DATFM/DA. In addition, from Fig. 9 (a), the average throughput in DATFM/DA is almost same as that in DATFM-area. These results indicate that DATFM/DA can achieve effective sensing and data transfer in the whole re-

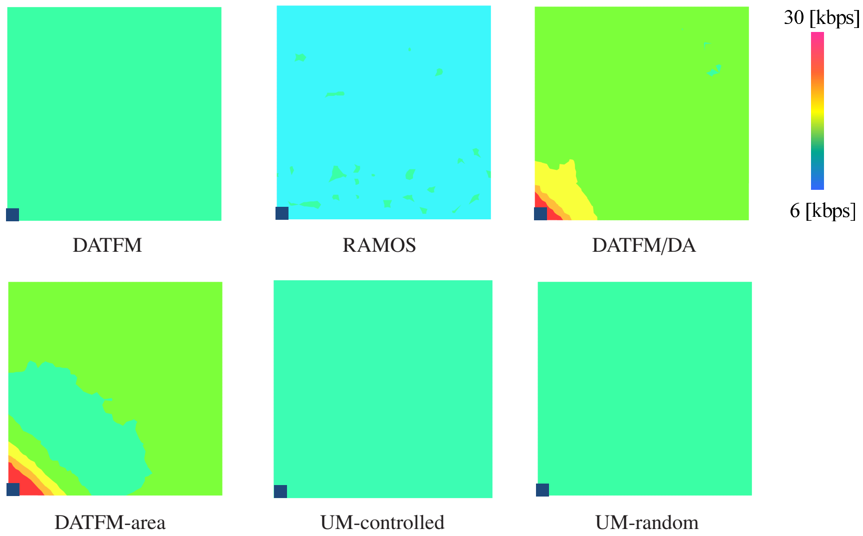


Fig. 8 Distribution of the throughput ($N_{\rm fix}$ = 10, $N_{\rm mov}$ = 40).

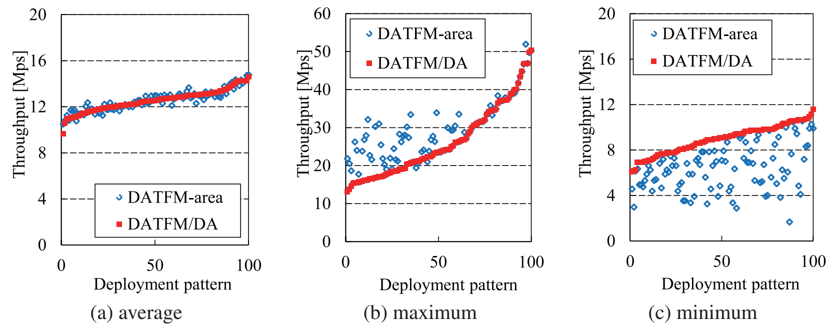


Fig. 9 Throughput in DATFM/DA and DATFM-area.

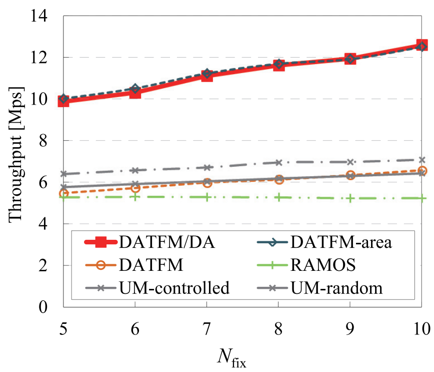


Fig. 10 The average throughput.

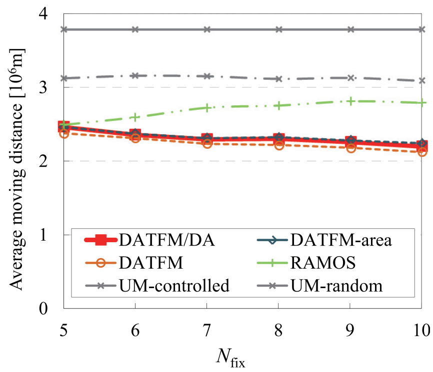


Fig. 11 The average moving distance.

gion.

5.3 Effects of $N_{\rm fix}$

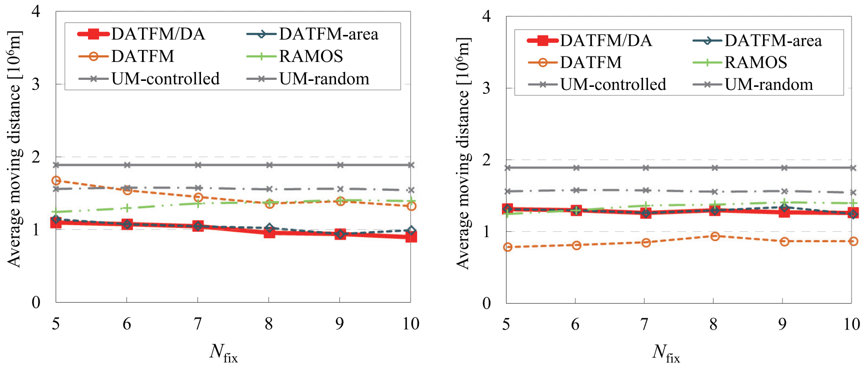
We evaluated the following two criteria when changing the number of fixed nodes, $N_{\rm fix}$:

- Throughput : The average amount of data that arrive at the sink node per 1 [sec].
- Average moving distance : The average of moving distances of all nodes during the simulation period.

Figures 10 and **11** show the simulation results. The horizontal axis on all graphs indicates the number of fixed nodes $N_{\rm fix}$. The vertical axis indicates the throughput in Fig. 10 and the average moving distance in Fig. 11. In the experiment, we set $N_{\rm mov}$ as 40.

Figure 10 shows that the average throughput in DATFM/DA is always larger than those in DATFM, RAMOS, UM-random, and UM-controlled. In addition, the average throughput in DATFM/DA is almost same as that in DATFM-area. This is due to the same reasons described in Section 5.2. Note that the minimum throughput in DATFM/DA always becomes larger than that in DATFM-area.

Figure 11 shows that the average moving distances in DATFM/DA and DATFM-area are slightly larger than that in DATFM although these methods are designed to reduce the moving distances of mobile nodes. As shown in Figs. 9 and 10, DATFM/DA and DATFM-area achieve a higher throughput than that in DATFM. This indicates that a large amount of data are quickly accumulated in each fixed node, and thus, data transmissions frequently occur. In such a situation, the frequent data



(a) For sensing operations.

(b) For data transmissions.

Fig. 12 The details of the average moving distance.

transmissions cause the increase of the moving distance. In order to validate this discussion, we illustrate the detail of the moving distance in **Fig. 12**. In this figure, the horizontal axis on all graphs indicates the number of fixed nodes N_{fix}. The vertical axis indicates the average moving distance for sensing operations in Fig. 12 (a), and that for data transmissions in Fig. 12 (b). Fig. 12 (a) shows that the moving distances for sensing operations in DATFM/DA and DATFM-area are always smaller than that in DATFM. This results in the increase of throughput. On the other hand, Fig. 12 (b) shows that the moving distances for data transmissions in DATFM/DA and DATFM-area are always larger than that in DATFM. This results in the increase of the moving distance.

6. Conclusion

In this paper, we proposed DATFM/DA, which is an extension of our previous method, DATFM. DATFM/DA divides the target region into multiple areas, and assigns a territory to each mobile node in order to alleviate the increase of the moving distance for a sensing operation. Moreover, DATFM/DA determines the number of mobile nodes deployed in each area in order to monitor the whole target region efficiently. We have also conducted the simulation experiments to evaluate the performance of DATFM/DA. The results show that DATFM/DA improves the performance compared with DATFM.

From the results in Fig. 8, DATFM/DA achieves a high throughput in the entire region. However, the difference between the maximum and the minimum throughput is still large. Thus, in order to apply our method to some applications which need to acquire data in the whole region uniformly, it is necessary to further extend our method. In addition, some applications may specify the required (minimum) throughput in the entire region. In such applications, it is not necessary for all the mobile nodes to perform sensing operations. For these applications, we plan to extend our strategy to control each mobile node. For example, it might be good to deploy some mobile nodes only for moving for data transmission.

In this paper, we use two types of sensor nodes, fixed nodes and mobile nodes. Here, the cost of preparing each of fixed and mobile nodes should be different according to the environment and application. Thus, when the total cost for the entire system is given, the performance depends on the ratio of the numbers of fixed and mobile nodes which can be realized in the allowed cost. As a part of our future work, we plan to investigate the effects of the cost for preparing each node on the performance of our proposed method.

Moreover, we have proposed DATFM/DF (DATFM with deliberate Deployment of Fixed nodes [15], which is another extension of our previous method, DATFM. DATFM/DF focuses on another aspect of DATFM, that is, the deployment of fixed nodes, and strategically determines the locations of fixed nodes. Since DATFM/DF and DATFM/DA apply different extensions to DATFM, a further improvement of efficiencies of sensing and data transfer is expected by considering both of these aspects together. Thus, we plan to discuss the integration of DATFM/DF and DATFM/DA.

We also plan to extend our method to handle node failures in order for our method to be applied to harsh environments. Moreover, we plan to implement our proposed method on real sensor nodes and verify its effectiveness on a practical platform.

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