A Node Deployment Method 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). 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 efficiencies of sensing and data gathering. Furthermore, we conduct simulation experiments to evaluate the performance of our extended method.

疎なセンサネットワークにおける移動型センサを用いた効果的なセンシングのためのセンサ配置手法

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本稿では，筆者らがこれまでに提案した移動型センサの制御手法である DATFM (Data Acquisition and Transmission with Fixed and Mobile node) の拡張手法を提案する．提案手法である DATFM/DF (DATFM with deliberate Deployment of Fixed nodes) では，DATFM の性能を数学的に解析し，その結果に基づいてセンサノードの配置を決定することで，センシングおよびデータ収集の性能を向上させる．さらに本稿では，シミュレーション実験によって，提案手法の有効性を評価する．

1 Introduction

Recent advance in wireless communication technology has led to an increasing interest in wireless sensor networks that are constructed of only wireless nodes that equip several sensor devices. On the other hand, with the development of robotics technologies in recent years, there have been many studies on sensors with a moving facility (*mobile sensors*) [4, 6]. Mobile sensors are well suited for a sparse environment since a large area can be monitored with a small number of sensor nodes.

Until now, there have been several studies on data transfer in mobile sensor networks [4, 6]. However, since data transfer is performed mainly by the movement of nodes especially in a sparse network, the performance of sensing and data gathering becomes significantly low.

To solve this problem, we have proposed an effective mobile sensor control method, named DATFM (Data Acquisition and Transmission with Fixed and Mobile node) [5]. 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. In addition, DATFM efficiently transfers the accumulated data by constructing a communication route of multiple mobile nodes between fixed nodes in DATFM.

Here, the performance in DATFM depends on the locations of fixed nodes. In this paper, we propose DATFM/DF (DATFM with deliberate Deployment of Fixed nodes) , which is a deliberate deployment strategy of fixed nodes based on the analysis of the effects of the locations of fixed nodes.

The reminder of this paper is organized as follows. In Section 2, we briefly introduce some conventional data transfer methods for mobile sensors. In Section 3, we explain the details of DATFM/DF proposed in this paper. The results of simulation experiments are presented in Section 4. Finally, we conclude this paper in Section 5.

2 Related work

In [3, 7], data transfer methods with mobile sensors have been proposed. The mobile nodes in these methods randomly move throughout the whole area and transfer data to a connected mobile node which is closer to the sink. These methods may not work well in the sparse network since they assume relatively dense environment.

In [4], RAMOS (Routing Assisted by Moving Objects) has been proposed as a data transfer method with mobile sensors. In RAMOS, each sensor transfers acquired data to the sink mainly by moving to the sink. Thus, the performance deteriorates in a large area.

In [6], a sensing method using uncoordinated mobile nodes (UM nodes) has been proposed. In this method, each UM node acquires data until the amount of the acquired data reaches the memory capacity. Moreover, each UM node exchanges information on the acquired data with a connected UM node and deletes the data which were acquired by the connected node at the same location and time. By doing so, duplicated sensing (sensing a location by multiple nodes) can be suppressed. However, since each UM node selects the destination randomly from the whole area, the moving distance to the destination tends to increase. Thus, the efficiency of sensing decreases in a large area.

3 DATFM/DF

To solve the problems of the conventional methods, we have proposed DATFM (Data Acquisition and Transmission with Fixed and Mobile node) [5] to improve efficiencies of sensing and data transfer in sparse sensor networks. DATFM achieves effective data acquisition and transmission by accumulating data on a fixed node before transferring them to the sink, and transmitting the accumulated data via a communication route constructed by multiple mobile nodes.

Here, since the distances between fixed nodes affect the number of required mobile nodes to construct a communication route, the performance of DATFM depends on the locations of fixed nodes.

In this section, we propose a deliberate deployment strategy named DATFM/DF (DATFM with deliberate Deployment of Fixed nodes). DATFM/DF further improves the performance of DATFM by deploying fixed nodes based on the analysis of the effects of the locations of fixed nodes. Here, the basic behaviors of nodes in DATFM/DF are same as those in DATFM (described in Subsections 3.1, 3.2, and 3.3).

3.1 Types of sensor nodes

In DATFM/DF, there are two types of sensor nodes, *fixed node* and *mobile 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 the nearby mobile nodes to construct a communication route when transmitting the accumulated data to the sink.

On the other hand, a mobile node moves around the area. In addition, it has the following three modes:

Sensing mode (*SM*): A node sets a destination (sensing point) and moves there. After reaching the destination, it performs the sensing operation and selects its new destination.

Collecting mode (*CM*): A node moves faster than that in *SM* in order to collect other mobile nodes to construct a communication route between fixed nodes.

Transmission mode (*TM*): A node constructs a route between fixed nodes and transfers the data.

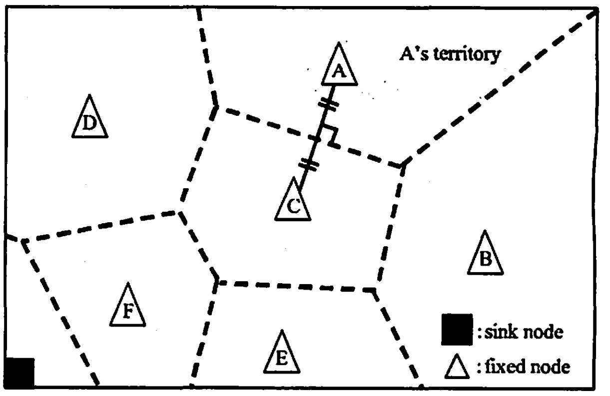

Figure 1: Territories of fixed nodes.

3.2 Moving strategy of mobile nodes

DATFM/DF divides the area into several regions based on a Voronoi diagram [1] in which fixed nodes are the site points as shown in Figure 1. In DATFM/DF, each site point (fixed node) has charge of the corresponding region. We call the region for each fixed node as its *territory*.

A mobile node basically sets its mode as *SM* and moves to its destination by the following steps:

1. It moves to connect to the nearest fixed node and transmits its acquired data.
2. It calculates the distances between its destination and all fixed nodes in the adjacent territories and moves to the fixed node that is the nearest to its destination. These procedures are repeated until the mobile node connects to the fixed node in the territory which involves the destination.
3. It moves to its destination and performs a sensing operation.

3.3 Data Transmission

A fixed node starts to transfer the accumulated data when the amount of the accumulated data 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).

Next, the source node sends a *route request* (*RReq*) to a mobile node that firstly connects to it and the mobile node changes the 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

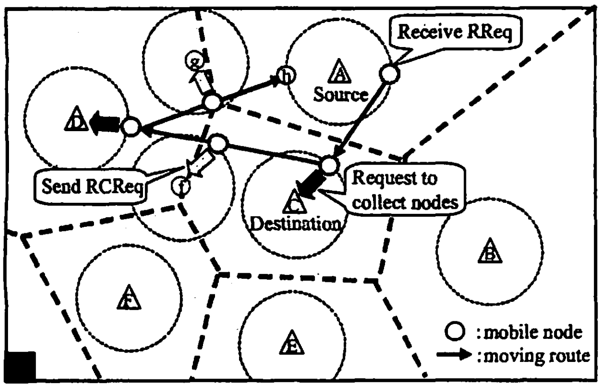

Figure 2: Collecting mobile nodes.

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*. Figure 2 shows an example of behaviors of a mobile node h in *CM* which received a *RReq* from the source node A. h moves to the adjacent 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 Figure 3. 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.

After transferred the accumulated data, the mobile nodes in *TM* change its mode into *SM*.

3.4 Deployment of Fixed Nodes

In DATFM/DF, fixed nodes are deployed according to five guidelines derived by the performance analysis.

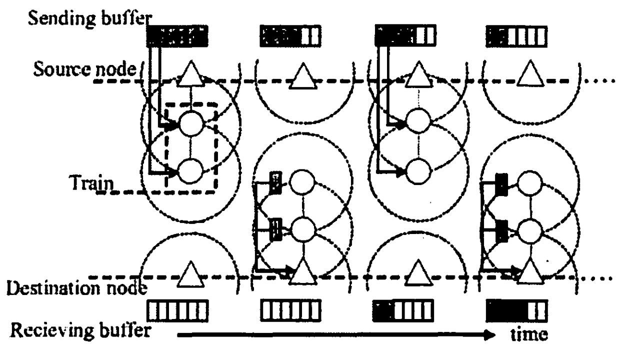

Figure 3: Train transmission.

Table 1: Given parameters.

Parameter	Value
i	IDs of fixed nodes (ID of the sink: 0).
$\mathbf{L}_i$	location of fixed node i.
$\mathbf{T}_i$	territory of fixed node i.
$\mathbf{d}_i$	location of the destination (sensing point) in $\mathbf{T}_i$ of a mobile node. ($\mathbf{d}_i \in \mathbf{T}_i$)
S_{area}	size of the whole area.
ν_m	velocity of mobile nodes in *SM*.
T_s	time for a sensing operation.
N_{mov}	number of mobile nodes in the whole area.
N_{fix}	number of fixed nodes in the whole area.
N_{req_i}	required number of mobile nodes to construct a route from fixed node i.

3.4.1 Analysis of DATFM

In the analysis, we discuss the *sensing rate* R_s, which is defined as the number of sensing operations per unit time in the whole area. Here, in order to simplify the analysis, we do not consider the cases of collecting mobile nodes by using mobile nodes in *CM*, and train transmission. In addition, the moving path to the fixed node which has charge of the destination (described in Subsection 3.2) can be roughly approximated as the straight line. Therefore, we assume that mobile nodes go straight to the fixed node (do not go through fixed nodes in the neighboring territories). Actually, the effect of the difference of moving to the analysis is small. Furthermore, we assume that parameters in Table 1 are given in advance.

First, R_s can be calculated as the inverse of the average times elapsed for a sensing operation. We call this time as the *average sensing cycle time* T_{cycle}.

T_{cycle} is represented as the sum of elapsed times for a mobile node to move from the connected fixed node to the fixed node in the territory where the destination exists, to move to the destination, to perform the sensing operation, and to move back to the fixed node (see Figure 4). Here, when each mobile node randomly chooses the destination from the whole area, the probability that a

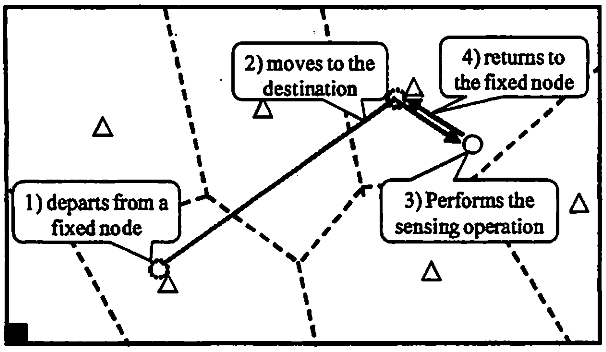

Figure 4: The operations of a mobile node in T_{cycle}.

mobile node comes from $\mathbf{T}_j$ and chooses the destination in $\mathbf{T}_i$ depends on the ratio of the size of $\mathbf{T}_j$ ($|\mathbf{T}_j|$) to the size of the whole area (S_{area}). Thus, T_{cycle} of a mobile node that performs the sensing operation in $\mathbf{T}_i$ (T_{cycle_i}) is:

$$\begin{aligned} T_{cycle_i} &= \sum_{j=0,j!=i}^{N_f} \frac{|\mathbf{T}_j|}{S_{area}} \cdot (\frac{|\mathbf{L}_i - \mathbf{L}_j|}{\nu_m}) \\ &+ \frac{2 \cdot ave|\mathbf{L}_i - \mathbf{d}_i|}{\nu_m} + T_s. \end{aligned} \quad (1)$$

Here, when each mobile node chooses its destination randomly from the whole area, the probability that a mobile node chooses the destination in $\mathbf{T}_i$ becomes the ratio of the size of $\mathbf{T}_i$ ($|\mathbf{T}_i|$) to S_{area}. Thus, the average sensing cycle time in the whole area (T_{cycle}) is derived by:

$$T_{cycle} = \sum_{i=0}^{N_f} \frac{|\mathbf{T}_i|}{S_{area}} \cdot T_{cycle_i}. \quad (2)$$

However, since each fixed node transfers data via a communication route constructed by mobile nodes, several mobile nodes cannot perform the sensing operation during the data transmission. Thus, we should consider the effect of data transmission. Let us define the *average number of free nodes* N_{free} that are not used for data transmission in a unit time. Then, R_s is defined as the ratio of free nodes to all mobile nodes.

$$R_s = \frac{1}{T_{cycle}} \cdot \frac{N_{free}}{N_{mov}}. \quad (3)$$

N_{free} can be calculated by using the total required number of mobile nodes to construct a communication route for each fixed node and the frequency of data transmission.

$$N_{free} = N_{mov} - (\alpha \cdot \sum_{i=1}^{N_f} N_{req_i}). \quad (4)$$

Here, we set the frequency of data transmission as a constant α for simplicity.

From the above discussion, R_s can be represented as follows:

$$R_s = \frac{1}{T_{cycle}} \cdot (1 - \sum_{i=1}^{N_f} \frac{\alpha N_{req_i}}{N_{mov}}). \quad (5)$$

3.4.2 Guidelines for deployment

From the result of analysis, we can see that R_s depends on the number of mobile nodes (N_{mov}), 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_{cycle}).

First, we discuss the relation between N_{mov} and $\sum_{i=0}^{N_{fix}} N_{req_i}$. The ratio of free nodes to all mobile nodes is represented by the following formula:

$$\frac{N_{free}}{N_{mov}} = 1 - \frac{\alpha \cdot \sum_{i=1}^{N_{fix}} N_{req_i}}{N_{mov}}. \quad (6)$$

When the above value becomes lower than zero, the network does not work. Therefore, the value must be larger than zero. Here, when each fixed node starts the data transmission every time it receives data from a mobile node, N_{free} becomes the minimum. In such a case, the frequency of data transmission α becomes the maximum, that is, 1. Therefore, we can derive the following constraint:

$$\begin{aligned} \frac{\sum_{i=1}^{N_{fix}} N_{req_i}}{N_{mov}} &\leq 1. \\ \sum_{i=1}^{N_{fix}} N_{req_i} &\leq N_{mov}. \end{aligned} \quad (7)$$

Thus, we can derive the following guideline:

Guideline 1 : *The total of N_{req_i} should be smaller than N_{mov}.*

Next, we discuss T_{cycle}. From eqs.(1) and (2), T_{cycle} 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_{cycle} becomes.

First, in order to decrease $ave|\mathbf{L}_i - \mathbf{d}_i|$, we derive the following guideline:

Guideline 2 : *The location of each 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 a proportional to $|\mathbf{T}_i|$ for simplicity.

$$ave|\mathbf{L}_i - \mathbf{d}_i| = \beta|\mathbf{T}_i|. \qquad (\beta : const.) \quad (8)$$

Thus, we can derive the following formula:

$$\sum_{i=0}^{N_{fix}}(|\mathbf{T}_i| \cdot ave|\mathbf{L}_i - \mathbf{d}_i|) = \sum_{i=0}^{N_{fix}}(\beta'|\mathbf{T}_i|^2). \quad (9)$$

In order to minimize this value, we calculate the partial differentiation of $\sum_i |\mathbf{T}_i|^2$ with respect to $|\mathbf{T}_i|$, and derive the following guideline (due to the limitation of space, we omit the detailed calculation):

Guideline 3 : *The territory size of each fixed node should be uniform* ($|\mathbf{T}_0| = |\mathbf{T}_1| = \cdots = |\mathbf{T}_{N_{fix}}|$).

From guidelines 2 and 3, N_{req} should be uniform for all is. Thus, we can derive the following formulae:

$$\begin{aligned}\sum_{i=0}^{N_{fix}} N_{req_i} \cdot r_{com} &= N_{fix} \cdot N_{req} \cdot r_{com}. \\ &\leq N_{mov} \cdot r_{com}. \\ \bar{N}_{req} \cdot r_{com} &\leq \frac{N_{mov}}{N_{fix}} \cdot r_{com}. \end{aligned} \quad (10)$$

Let us define the above value $N_{mov} \cdot r_{com}/N_{fix}$ as the *maximum length of communication route* L_{max}. This indicates the following guideline:

Guideline 4 : *The distance between each fixed node and its destination node should be less than or equal to* L_{max}.

However, if we follow the above guideline, most fixed nodes are deployed near the sink in a sparse network (i.e. N_{mov}, N_{fix}, and r_{com} are very small). This may cause the increase of the difference of territory sizes. Therefore, we should set the following guideline in order to suppress such an undesirable increase of the difference of territory sizes:

Guideline 5 : *Some fixed nodes should be deployed at locations which are far from the sink with high priority.*

3.4.3 Deployment Strategy

Based on the above guidelines, we devise the following strategy for deploying fixed nodes:

1. Define the ideal territory size as S_{all}/N_{fix} (from Guideline 3).
2. Calculate the ideal length of the communication route L_{ideal} by the following formula (from Guidelines 2 and 3):

$$L_{ideal} = 2 \cdot \sqrt{\frac{S_{all}}{\pi \cdot N_{fix}}}. \quad (11)$$

   In the above formula, we assume the shape of each territory as a circle for simplicity.
3. Compare L_{ideal} and L_{max} and adopt the smaller one as the effective length of communication route L_{eff} (from Guidelines 1).

$$L_{eff} = min(L_{ideal}, L_{max}). \quad (12)$$

4. Calculate the required number of fixed nodes in order to deploy a fixed node at the farthest point from the sink when the distance between the fixed nodes is set as L_{eff} (from Guideline 4). We define this value as N_{hop}.

$$N_{hop} = \lfloor \frac{|\mathbf{T}_0 - \mathbf{d}_{max}|}{L_{eff}} \rfloor. \quad (13)$$

   In the above formula, $\mathbf{d}_{max}$ denotes the location of the farthest point from the sink.
5. When the total number of fixed node is smaller than N_{hop}, deploy all fixed nodes on the line segment between $\mathbf{L}_0$ and $\mathbf{d}_{max}$ at intervals of L_{eff}. Otherwise, make all patterns of deployment of fixed nodes that the number of fixed nodes on the largest communication route (set of transmission routes from a fixed node to the sink) is more than or equal to N_{hop}.
6. Adjust the locations of each fixed nodes in order to uniform the size of each territory (from Guideline 3) while keeping the distance between each pair of source and destination nodes.

Here, specific procedure of the adjustment of location is not defined in our strategy (Currently, we apply a trial-and-error approach). The study of the effective procedure is our future work.

4 Performance evaluation

In this section, we show the results of the simulation experiments regarding performance evaluation of DATFM/DF. In the simulation experiments, we compare the performances of DATFM, DATFM/DF and UM [6].

4.1 Simulation environment

In the simulation experiments, we deploy sensor nodes in a 1,000[m] $\times$ 1,000[m] flatland. Each sensor node does a sensing operation with the rate of 1,000[bit/sec $\cdot$ m^2]. The wireless communication range and the channel bandwidth are 50[m] and 3[Mbps], respectively.

There are 10 fixed nodes except for the sink and N_{mov} mobile nodes ($30 \leq N_{mov} \leq 50$). 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 1,000[Mbit] and 10[Mbit], respectively. Each fixed node starts data transmission when the amount of the accumulated data exceeds 400[Mbit].

In UM, there are (10 + N_{mov}) UM nodes. Each UM node has a memory space whose size is 10[Mbit]. Each node moves with velocity of 5[m/s] when sensing, and 10[m/s] when transferring data. Each UM node starts transferring data to the sink when the amount of the accumulated data exceeds 10[Mbit].

In this environment, we evaluate the following two criteria during 60,000[sec]:

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

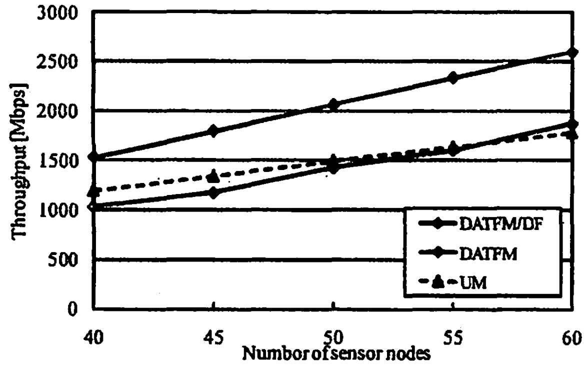

Figure 5: Throughput.

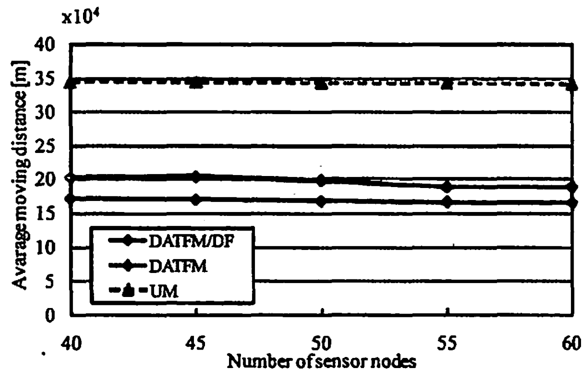

Figure 6: Average moving distance.

4.2 Evaluation results

Figures 5 and 6 show the simulation results changing the total number of sensor nodes ($10 + N_m$). The horizontal axis on both graphs indicates the total number of sensor nodes. The vertical axes respectively indicate throughput in Figure 5 and average moving distance in Figure 6.

Figure 5 shows that the throughput in DATFM/DF is always larger than that in DATFM. Thus, we can see that the deployment strategy is effective to improve the efficiencies of sensing and data transfer. Moreover, the throughput in DATFM/DF is larger than that in UM. This is because acquired data in DATFM/DF is accumulated on a fixed node before transferred to the sink, whereas nodes in UM move to the sink every time they acquire data. Here, the throughput in DATFM is not so large compared with that in UM. This is because, since fixed nodes in DATFM are randomly deployed in the whole area, it may become difficult for some fixed nodes to construct a communication route.

Figure 6 shows that the average moving distances in DATFM and DATFM/DF are always smaller than that in UM. This is because in DATFM and DATFM/DF, mobile nodes that acquire data do not need to move to the sink, whereas mobile sensors in UM have to move to the sink every time they acquire data. Moreover, the moving distance in DATFM/DF is always smaller than that in DATFM. This is because the deployment strategy in DATFM/DF aims to reduce the average distance between fixed nodes.

From the above results, DATFM/DF can transfer data with smaller moving distance than DATFM and UM. Here, in mobile sensor networks, the energy consumed by movement is much larger than those by communication and computation [2]. Therefore, we can see that DATFM/DF achieves high throughput and energy-efficiency compared with DATFM and UM.

5 Conclusion

In this paper, we proposed DATFM/DF to further improve efficiencies of sensing and data transfer from 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 the performance compared with DATFM.

As part of our future work, we plan to consider a concrete procedure for adjusting of locations of fixed nodes in order to further improve the performance in DATFM/DF.

Acknowledgement

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