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NODE CONTROL METHODS TO REDUCE POWER CONSUMPTION USING PUSH-BASED BROADCAST FOR MOBILE SENSOR NETWORKS

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Recently, a lot of researchers have directed their attention to mobile sensor networks that are constructed by sensor nodes with a moving facility. Mobile sensor networks enable to construct a wide-range sensing system by the cooperative behaviours of a small number of mobile sensors. However, because radio communication range of the nodes does not cover the whole sensing area, every node has to move closer to the sink to deliver its sensor readings. Thus, the power consumption to deliver the sensed data to the sink becomes large. We previously proposed two mobile sensor control methods to reduce the power consumption by employing push-based broadcast, named the MST (Moving-distance-based Static Topology) and the SR-N (Shortest Route with Negotiation) methods for sparse mobile sensor networks. In this paper, we propose the MST/NFD (MST with Node Failure Detection) and the SR-N/NFD (SR-N with Node Failure Detection) methods as extensions of the MST and the SR-N methods to detect node failures. We also conducted simulation experiments to evaluate the performance of our methods and confirmed that the MST/NFD method is more robust over node failures than the SR-N/NFD method, and that the SR-N/NFD method can achieve the high throughput than the MST/NFD method.

Key words: Mobile Sensor Networks, Push-based Broadcast, Power Consumption

1 Introduction

Recent technological advances in wireless communication and semiconductors have led to improvements in radio communication devices, which have become smaller and lighter and have higher performance. Because of these improvements, much research has been done on sensor networks consisting of small sensor nodes equipped with wireless communication devices [1-4]. Sensor networks are expected to be used for many applications such as environmental monitoring [5, 6], investigation of plants and animals [7, 8], and environmental control in office buildings [9, 10].

Moreover, wireless multimedia sensor networks have attracted much attention due to the availability of inexpensive devices such as CMOS cameras and microphones that are able to capture multimedia content from the environment [11, 12]. Wireless multimedia sensor networks will enhance existing sensor network applications [13, 14]. In sensor networks, sensor nodes deliver their acquired data to the data sink by using multi-hop communication. Traditional research in sensor networks typically treats unmovable nodes that stay in fixed positions. On the other hand, because of the advancement of robotics technology in recent years, there has been increasing interest in research on sensor networks that consist of sensors equipped with actuators (mobile sensor nodes)[15-17].

If nodes are fixed, many nodes need to be deployed to cover the whole sensing area. Additionally, fixed nodes are difficult to deploy in large areas or in environments where people cannot enter, such as disaster sites and heavily polluted areas. In such environments, even if nodes are deployed from the air (e.g., from airplanes or helicopters), it is difficult or even impossible to deploy nodes in the positions where we want to do sensing. Therefore, mobile sensors are well suited for such environments. That is, a small number of mobile sensors can go into such large areas and perform sensing operations at various positions freely. Here, note that nodes may not be within radio communication ranges of each other, thus, these nodes need to move closer to the data sink for transmitting their sensor readings, and the power consumption to deliver the data to the data sink increases.

In this paper, we assume that every node in the sensor network is a mobile sensor node, and propose two methods to deliver the sensed data to the data sink by using multi-hop communication by forcing nodes to construct a temporal network. Both methods achieved the low power consumption by reducing the moving distance for each node to deliver the sensed data to the data sink. The first one is the *moving-distance-based static topology with node failure detection (MST/NFD) method*, in which each node moves to the same position for delivering the sensed data to the data sink. The position is determined so that every node takes the shortest route to move from its sensing position to the position connecting to the temporal network. If the data sink detected a node failure, it directs another node to move the position of the failed node connecting the temporal network in order to maintain the temporal network by using push-based broadcast. The second one is the *shortest route with negotiation and node failure detection (SR-N/NFD) method*, in which nodes decide positions to construct a network according to the situation at that time. In this method, we control movement of nodes by using push-based broadcast. Nodes receive the information on the positions of other nodes through the broadcast so that the nodes can move to the nearest positions where they can communicate with the data sink by using multi-hop communication, i.e., join to the temporal network for data transmission. If the data sink detected a node failure, it directs the other nodes to go back sensing positions after receiving their sensed data.

The remainder of this paper is organized as follows: in Section 2, we summarize the related works on mobile sensor networks. Section 3 presents the assumed environment, and section 4 describes our proposed method. The results of simulation experiments are shown in section 5. In section 6, we conclude the paper.

2 Related Works

Several data gathering strategies in mobile sensor networks have been proposed. We present some typical related studies in this section.

Moore et al. have proposed an approach to command mobile sensors to collect samples of the distribution of interest, and then use these samples to determine new sampling locations of each sensor [18]. This study paid more attention to estimate the distribution of sensor readings than the energy consumption.

Shah et al. have proposed Data MULE [19], an architecture for collecting data in sparse sensor networks. Data MULE uses mobile entities in the environment to transport data from sensor nodes to access points. Data MULE aims to achieve energy saving in sensor nodes by using short-range radios. Similarly, Zhao et al. have proposed a message ferrying approach in order to delivery data in sparse mobile ad hoc networks [20]. These studies adopt a set of special mobile node with large memory to deliver sensor readings to data sink. It is therefore important to decide or predict the trajectory of the special nodes.

Vincze et al. have pointed out that selecting the optimal moving positions for mobile sinks is an NP-hard problem and have proposed a heuristic algorithm to determine the moving direction and distance [21]. The algorithm is more suitable for event-driven applications, such as detecting targets, rather than data-gathering applications where all sensor nodes report sensed data periodically.

Suzuki et al. have proposed the RAMOS (Routing Assisted by Moving Objects) [22]. RAMOS assumes the existence of a sink node, and each mobile sensor transfers its acquired data by moving to the sink node directly. Since each mobile sensor has to move to the sink node every time it gets data, movement cost drastically increases and the efficiencies of sensing and data transfer deteriorates in a sparse network.

Our previous work [23] adopted push-based broadcasting in order to inform the positions of other sensor nodes, and proposed methods to save energy and enhance throughput by reducing moving distance of sensor nodes. However, this study assume an ideal environment where node failures do not occur.

3 Assumed Environment

Figure 1 shows the environment assumed in this paper. We assume one data sink and multiple mobile sensor nodes are in the sensing area. Each sensor node knows the position of the data sink, its sensing position, and the total number of sensor nodes. Additionally, it can precisely acquire its current location by using a GPS or other methods in real time. As shown in Figure 1, the distance between nodes that are engaged in a sensing operation is usually larger than the radio communication range of node, so they cannot communicate with the data sink or other nodes if they stay in their sensing positions. Thus, they have to move to communicate with others and deliver their sensor readings to the data sink. When delivering data, they construct a network that can communicate with the data sink by using multi-hop communication. We call this network a *gathering network*. After all nodes participate in the gathering network and they finishes sending and relaying data, they start to move to their sensing positions again.

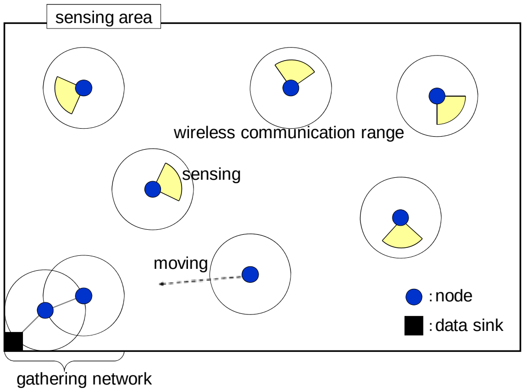


Figure 1 Assumed Environment.

Moreover, the data sink has a broadcast facility for push-based broadcast, where the broadcast area covers the whole sensing area. It also knows the sensing positions of all nodes.

4 Proposed Methods

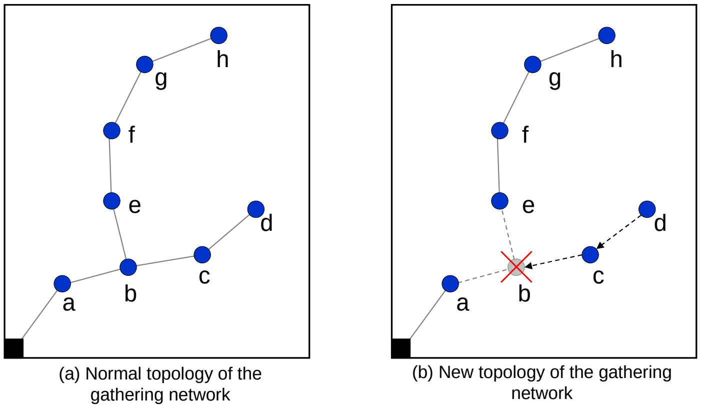
In this section, we present two mobile sensor control methods which we proposed in this paper.

4.1. MST/NFD (Moving-distance-based Static Topology with Node Failure Detection) method

4.1.1. Basic Behaviour (MST method)

In the MST method [23], we focus on only reducing the moving cost of nodes as much as possible. Thus, the position of each node in constructing a gathering network is determined beforehand, and the node always moves to the position to deliver its sensed data. We call the position *delivering position*. When the node finishes its sensing, it moves to its delivering position and stop there. Each node delivers its sensed data to the data sink when it can communicate with the data sink by using multi-hop communication. The delivering positions of nodes are determined by the following procedure:

1. Each node is placed at its assigned sensing position.
2. Every node that has not joined the gathering network yet selects the nearest node among all nodes that already joined the gathering network and their delivering positions are closer to the data sink than the sensing position of the node.
3. Every node calculates the distance from its sensing position to the closest position where the node can communicate with the node selected in step 2. We call this *moving distance*.
4. The node whose moving distance is the shortest joins the gathering network.
5. Step 2, 3, and 4 are repeated until all nodes join the gathering network.



(a) Normal topology of the gathering network

(b) New topology of the gathering network

Figure 2 Example of modification of the gathering network when node failure occurred in the MST/NFD method.

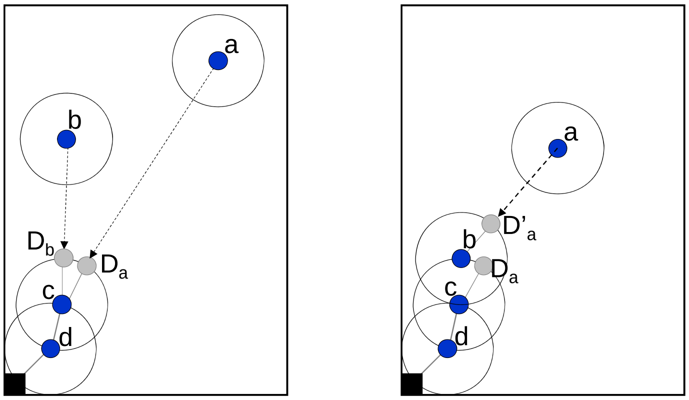
4.1.2. Node Control When Node Failure Occurs in the MST/NFD method

In the MST method, to reduce the moving distance of every node, each node that finished sending and relaying data starts going back to its sensing point after all nodes participated in the gathering network. If node failures occur, some nodes cannot leave the gathering network. To solve this problem, the data sink predicts the time when each node participates in the gathering network (we call the time the *arrival time*), and assumes that nodes fail if they did not participate in the gathering network until their estimated arrival times. Similarly, we call the time when each node left the gathering network the *departure time*. Each node migrates between its sensing position and its delivering position. Since the moving time and the sensing time of each node are constant in an ideal environment, it is easy for the data sink to predict the arrival time of each node. The data sink calculates the estimated $(k+1)$-th arrival time $Ta'_{n,k+1}$ of node n using the following equation:

$$Ta'_{n,k+1} = Td_{n,k} + ts + tm_n \tag{1}$$

where $Td_{n,k}$, ts and tm_n are the k-th departure time of node n, the sensing time and the round-trip time of node n moving between its sensing position and delivering position, respectively. If a node has not participated in the gathering network at its arrival time, the data sink judges that the node has broken down. In this case, a new node is put at the sensing position of the broken node so that the system can keep observing all sensing positions. Then, the data sink orders nodes to change their delivering positions by broadcasting. More specifically, to reduce the total of moving cost of nodes due to the modification of the gathering network, each node on the path with the least number of nodes between the failure node to a leaf node moves to the delivering position of a node with which it was supposed to connect. After that, the data sink updates the arrival time of nodes which changed their delivering positions by the following equation:

$$Ta''_{n,k+1} = Ta'_{n,k+1} + \frac{d_{com}}{v} \tag{2}$$



(a) before changing destination (b) after changing destination

Figure 3 Basic behaviour of nodes in the SR-N method.

where $Ta''_{n,k+1}$, d_{com}, and v are the updated $(k+1)$-th arrival time of node n, the communication range of nodes, and the node velocity.

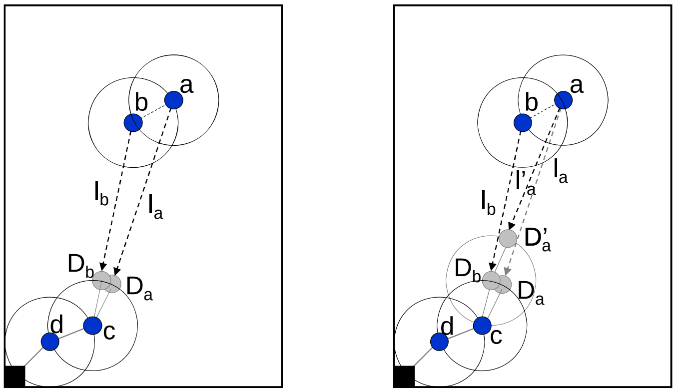
Figure 2 shows how to change the delivering positions of nodes when a node failure occurred. When node b broke down, the number of nodes on the path from node b to node d is smaller than that to node h, thus, nodes c and d move to the delivering positions of nodes b and c, respectively.

4.2. SR-N/NFD (Shortest Route with Negotiation and Node Failure Detection) Method

4.2.1. Basic Behaviour (SR-N method)

In the SR-N method [23], to construct the gathering network, the data sink broadcasts the information on the positions of nodes that have already connected to the gathering network so that other nodes can move based on the information. In the example shown in Figure 3(a), according to the broadcast information, nodes a and b that finished their sensing operations determined their destinations D_a and D_b, where they can communicate with the data sink by using multi-hop communication, and they start to move to the destinations. In Figure 3(a), dotted arrowed lines show the movement locus of the nodes, and D_a (D_b) shows the destination of node a (b). The broadcast information is updated when new nodes participate in the gathering network. As shown in Figure 3(b), when node b participates in the gathering network, it becomes the nearest node for node a, so node a changes its destination from D_a to D'_a. In this way, nodes dynamically change their destinations, resulting in shortening the moving distance to join the gathering network. When a node in the gathering network knows that all nodes participate in the gathering network and it finishes sending and relaying data, it returns to its assigned sensing position.

Nodes exchange information on their destinations when they can communicate with each other during migration toward the data sink. On the basis of the information, they decide their destinations that decrease the sum of their moving distance. Consequently, the total moving distance to construct the gathering network decreases; thus, the total power consumption is also reduced.



(a) before changing destination (b) after changing destination

Figure 4 Negotiation between single nodes.

In the next clause, we explain the details of the behaviours of the nodes in constructing the gathering network.

4.2.2. Negotiation Between Single Nodes

Figure 4 shows a situation where a node encounters another node while moving to the destination. In this figure, l_a (l_b) denotes the distance to the destination of node a (b). When nodes a and b move to connect with node c in the gathering network, they come close and can communicate with each other. Then, they update their destinations using the following procedure:

1. Nodes a and b, which can communicate with each other, exchange the information of their destinations D_a and D_b.
2. They calculate the moving distance l_a and l_b from the positions of the nodes to their destinations, and the node whose moving distance is longer than that of the other makes the other a candidate to connect the gathering network. In this figure, because $l_a > l_b$, node a makes node b a candidate to connect the gathering network.
3. Node a calculates the position D'_a, where it will be able to connect to node b in the gathering network, and the distance l'_a from its current position to D'_a. If $l'_a > l_a$, it changes its destination to D'_a.
4. If node a changes its destination in step 3, it sends the information on the position of its new destination D'_a to node b. Then, nodes a and b move jointly as a node group.
5. After that, if node b changes its destination, it sends the information on the position of its new destination to node a. Node a also changes its destination based on the information from node b. Node a does not change its destination even if it receives the broadcast information.

When more than two nodes encounter each other at the same time and can communicate among other nodes, each node determines whether it changes its destination. This process is performed successively from the node whose moving distance is the shortest to the longest.

We call the node that changed its destination to connect the other node a *child node* and the other node a *parent node*. In Figure 4, nodes a and b become a child node and a parent node, respectively.

If a node group and a single node encounter, or when two node groups encounter each other, they also change their destinations in the same way.

4.2.3. Keeping Distance Between Nodes in Node Group

As a result of a preliminary evaluation of the SR-N method, we found that the distance between nodes in the gathering network becomes shorter than the communication range of nodes, and extended the SR-N method to keep distances between the nodes [24]. In this extended method, a child node calculates the distance between its parent node and itself, and moves to its destination while keeping an appropriate distance from its parent node. Specifically, a child node moves according to the following procedure:

1. When a node joins a node group as a child node, the child node stays there if its parent node stays or if the distance between it and its parent node is shorter than $X\%$ of its wireless communication range.
2. The child node starts moving when the distance between it and its parent node equals its wireless communication range. If the distance becomes shorter than $X\%$ of its wireless communication range while moving toward the gathering network, it stays there.
3. When the parent node starts moving, it sends its child nodes a message that it has started moving.
4. When the child node receives the message from its parent node, it starts moving after the distance between it and its parent node equals its wireless communication range.

4.2.3. Node Control When Node Failure Occurs in the SR-N/NFD method

When node failures occur, a similar problem arises in the SR-N method as the MST method. In other words, some nodes cannot leave the gathering network. To solve this problem, in the SR-N/NFD method, the data sink also predicts the arrival times of all nodes, and assumes that nodes fail if they did not participate in the gathering network until their estimated arrival times. Then, the data sink allows other nodes to leave the gathering network.

Specifically, the data sink estimates $(k+1)$-th arrival time $Ta'_{n,k+1}$ of node n using the following equation:

$$Ta'_{n,k+1} = Td_{n,k} + \max_{i=2}^{k}\left(Ta_{n,i} - Td_{n,i-1}\right) \tag{3}$$

where $Ta_{n,k}$ and $Td_{n,k}$ are the k-th arrival time and the departure time of node n, respectively.

In equation (3), the data sink predicts the next arrival time with the maximal value of the past elapsed times (from when node n leaves the gathering network until when it participates in the gathering network again); thus, the data sink reduces the number of misjudgements of node failures as much as possible.

Here, the data sink cannot predict the first and second arrival time because it cannot use the information of the past elapsed times. Therefore, the data sink sets the predicted arrival time of the first participation as the sum of the sensing time and the movement time from the sensing position to the position where the node can communicate with the data sink directly. The predicted arrival time of the second participation is set as the sum of the movement time from the position where the node left the gathering network to the sensing position, the sensing time, and the movement time from the sensing position to the position where the node can communicate with the data sink directly.

When a node has not participated in the gathering network for successive two times of data gathering, the data sink judges that the node has broken down completely. In this case, a new node is put at the sensing position of the broken node so that the system can keep observing all sensing positions. Then, the new node starts to perform a sensing operation.

5 Performance Evaluation

In this section, we show the results of the simulation experiments regarding the performance evaluation of our proposed methods.

5.1. Simulation Environment

Table 1 shows the parameters and values used in our experiments. The sensing area was a flatland, and we allocated one data sink at one corner of the area. Sensing position of each node was given randomly and not changed. We initially allocated each node at its sensing position, and it started sensing once the simulation began. Each node took 1,000 seconds for each sensing operation and obtained data of 5 Mbit. For each node, the moving cost was 1 J/m, and the data sending cost $Ps(k,d)$ and the data receiving cost $Pr(k)$ were defined using the following equations:

$$Ps(k,d) = (k \cdot 50) + (0.1 \cdot k \cdot d^2) \text{[nJ]} \tag{2}$$

$$Pr(k) = k \cdot 50 \text{[nJ]} \tag{3}$$

Here, k [bit] is the size of the data that a node sends and receives, and d [m] is the distance between the source and destination of the data transmission. If a node sends data obtained in one sensing operation to another node that is 50 meters away, the data sending cost is 1.5 J. Here, the moving cost and the data sending and receiving costs in our simulations were also used in [25] and [26]. We did not take other costs into consideration because they are much lower. Additionally, we assumed that nodes

Table 1 Parameters

Prameter	Value
Size of sensing area	2,000[m] x 2,000[m]
Number of nodes	400
Node Velocity	1[m/s]
Communication range	50[m]
Communication speed	2[Mbps]
Simulation time	200,000[sec]

can send and receive data simultaneously and that there is neither delay nor fault in communication. When m nodes n_i $(1 \leq i \leq m)$ send their data at the same time to one node whose network bandwidth is S [Mbps], the transmission speed of node n_i is limited to S/m [Mbps].

First, we evaluated the MST/NFD and the SR-N/NFD methods when node failures do not occur with the following three criteria, where X in the SR-N/NFD method was set as 99.

Average cost:

The average of each of the moving, data sending, and data receiving costs per node. The total cost denotes the sum of these costs.

Throughput:

The average amount of data that arrived at the data sink per second.

Average communication distance:

The average of the communication distances of all nodes participating in the gathering network.

Then, we evaluated the MST/NFD and the SR-N/NFD methods when node failures occur with the following three criteria. We investigated the impact of the number of node failures occurred in each cycle of data gathering.

Wasted waiting time:

The total of the elapsed time during when each node in the gathering network waited until the nodes that actually failed participated in the gathering network, after each node in the gathering network finished sending and relaying the data to the data sink.

Throughput:

The average amount of data that arrived at the data sink per second.

Moving distance:

The average of the moving distances per node.

5.2. Comparison between the MST/NFD and the SR-N/NFD Methods Without Node Failures

First, we compare the MST/NFD and the SR-N/NFD methods where no node failure occurs. Table 2

Table 2 Comparison between the MST/NFD and the SR-N/NFD methods.

	MST/NFD	SR-N/NFD
Moving cost [J]	15,174	52,168
Sending cost [J]	5,512	5,281
Receiving cost [J]	908	867
Total cost [J]	21,594	58,316
Throughput [kbps]	910	979
Communication distance [m]	49.2	48.0

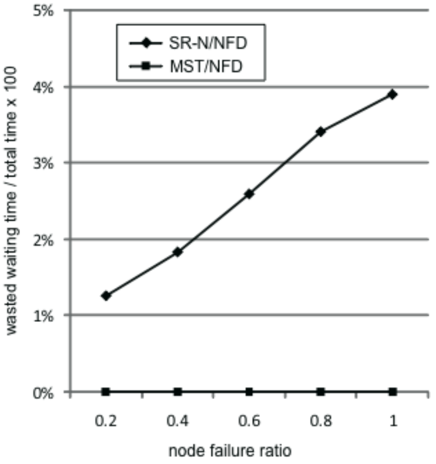


Figure 5 Ratio of wasted time to total time.

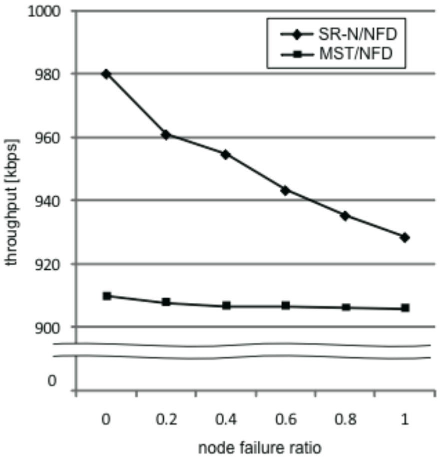


Figure 6 Throughput in the MST/NFD and the SR-N/NFD methods.

shows the average cost, throughput, and average communication distance. As shown in the table, since the delivering position of each node is greedily decided as a short moving distance in the MST/NFD method, the moving cost in the MST/NFD method is much lower than that in the SR-N/NFD method, and the communication distance in the MST/NFD method is longer than that in the SR-N/NFD method. However, nodes near the data sink have to always receive and forward the data of many other nodes because the delivering position of each node is fixed in the MST/NFD method. Hence, since these nodes cannot leave the gathering network and start sensing, the throughput in the MST/NFD method is lower than that in the SR-N/NFD method.

5.3. Comparison Between the MST/NFD and the SR-N/NFD Methods With Node Failures

Figures 5, 6, and 7 show the wasted waiting time, the throughput, and the moving distance in the MST/NFD and the SR-N/NFD methods, respectively.

In the MST/NFD method, even if the node failure ratio increases, the wasted waiting time and the throughput are almost constant. This method takes nodes near the data sink long time to relay the data of other nodes, thus, if these nodes break down and do not arrive at their delivering positions on time, the data sink cannot immediately detect the node failures because the routes from the data sink to these node are not established yet. Moreover, for the same reason, most nodes have to wait to deliver their sensed data. Therefore, the wasted waiting time is short in the MST/NFD method and there is little drop in the throughput. There is little change in the moving distance because the MST/NFD method keeps the number of nodes that change their delivering positions to a minimum.

In the SR-N/NFD method, the throughput degrades as the node failure ratio increases because the wasted time becomes long. However, even if the node failure ratio is 1 (Each node must break down once during the simulation.), the throughput in the SR-N/NFD method is higher than that in the MST method. The moving distance per one sensing increases as the node failure ratio increases.

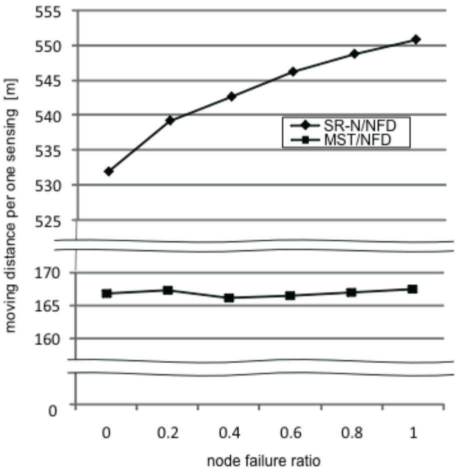


Figure 7 Moving distance per one sensing in the MST/NFD and the SR-N/NFD methods.

Consequently, we can confirm that the MST/NFD method is more robust over node failures. By using the SR-N/NFD method, while the moving distance and the wasted waiting time increase, the high throughput can be achieved.

6 Conclusion

In this paper, we proposed and evaluated two node control methods for a sparse mobile sensor networks, named the MST/NFD and the SR-N/NFD methods. In our methods, nodes construct a temporal network and communicate with the data sink by using multi-hop communication. In the SR-N/NFD method, each node dynamically determines its connecting point in the temporal network based on broadcasted information and migrates keeping a certain distance between other nodes to decrease the moving distance. Moreover, while the moving distance and the wasted waiting time increase when node failures occurred, the high throughput can be achieved. In the MST/NFD method, while the throughput is lower than that in the SR-N/NFD method, the moving distance is much shorter. Moreover, the MST/NFD method is robust over the node failures.

As part of our future work, we plan to extend our methods to further reduce the wasted waiting time and evaluate our methods on a practical platform.

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