Battery-Aware Algorithms for Mobile Relay and Route Construction on Wireless Sensor Network

Noritaka Shigei*, Issei Fukuyama*†, Hiromi Miyajima*‡, and Yogi Anggun Saloko Yudo§

***Abstract*—Multi-hop communication is used for prolonging the lifetime of WSN (Wireless Sensor Network). In recent years, mobile relay has been studied. The concept of mobile relay is that the mobile nodes change their locations so as to minimize the total energy consumed by both wireless transmission and locomotion. The conventional methods, however, do not take into account the remaining energy on mobile nodes, and as a result they do not always prolong the network lifetime. In this paper, we present battery-aware algorithms for mobile relay and initial route construction. All the presented algorithms take into account node's battery levels. For mobile relay, given a sequence of relaying nodes, our algorithms determine the movement of relaying nodes according to not only the total cost of movement and communication but also their battery levels. Initial route construction is needed for determining the sequence of relaying nodes, which is provided to mobile relay algorithms. For initial route construction, our algorithm avoids using nodes with low battery levels according to not only their communication costs but also their battery levels. The effectiveness of the proposed methods is demonstrated by simulations.**

***Index Terms*—mobile sensor node, wireless sensor network, multi-hop communication, network lifetime, battery-aware**

I. Introduction

THe wireless sensor network (WSN) is a key component for ubiquitous computing[1]. A WSN consists of a number of sensor nodes. Each sensor node senses environmental conditions such as temperature, pressure and light, and it sends the sensed data to a sink node or a base station, which is a long way off in general. Since the sensor nodes are powered by limited power batteries, in order to prolong the life time of the network, low energy consumption is important for sensor nodes. In general, radio communication consumes the most amount of energy, which is proportional to the data size and proportional to the square or the fourth power of the distance.

Thanks to the advance in mobile sensor platform technology, in recent years, it has been taken into attention that mobile elements are utilized to improve the WSN's performances[2] such as coverage[3], connectivity[4], reliability[5] and energy efficiency[6], [7]. Mobile relay has been studied in order to reduce the energy consumption in WSNs[8], [9]. The concept of mobile relay is that the mobile nodes change their locations so as to minimize the total energy consumed by both wireless transmission and locomotion. The conventional methods, however, do not take into account the battery level, and as a result they do not always prolong the network lifetime.

In this paper, we present battery-aware algorithms for mobile relay and initial route construction. All the presented algorithms take into account node's battery levels. For mobile relay, given a sequence of relaying nodes, our algorithms determine the movement of relaying nodes according to not only the total cost of movement and communication but also their battery levels[10]. The algorithms are presented for single data flow case and multiple data flow case. Further, as new contribution in this paper, we propose battery-aware algorithm for initial route construction. Initial route construction is needed for determining the sequence of relaying nodes, which is provided to mobile relay algorithms. Our algorithm avoids using nodes with low battery levels according to not only their communication costs but also their battery levels. This algorithm can be applied to any types of multi-hop communication such as relay with stationary nodes, battery-unaware mobile relay and battery-aware mobile relay, and it can prolong the network lifetime. The effectiveness of the proposed methods is demonstrated by simulations.

II. Mobile WSN Model

In this paper, we consider a similar WSN model as in [8], [9]. The network consists of N mobile nodes. The mobile node is assumed to have the following functions and features: 1) sensing environmental factors such as temperature, pressure and light, 2) data processing by low-power microcontroller, 3) a radio communication function in which the transmission power is controlled according to the distance to the target node, 4) powered by a limited life battery, 5) their own location can be estimated by an equipped GPS unit or other system, and 6) movable by an equipped electric motor.

The energy consumption model is as follows. When a mobile node moves a distance of d [m], it consumes the following energy

$$E_{\mathrm{M}}(d) = k \cdot d \quad [\mathrm{J}], \tag{1}$$

where the parameter k [J/m] depends on the mobile platform and the moving velocity. When a node transmits a data of m [bit] over a distance of d [m], it consumes the following energy

$$E_{\mathrm{T}}(d, m) = m(a + b \cdot d^2) \quad [\mathrm{J}], \tag{2}$$

where the parameters a and b depend on the environment and the radio platform. Further, when a node receives a data of m [bit], it consumes the following energy

$$E_{\mathrm{R}}(m) = c \cdot m \quad [\mathrm{J}], \tag{3}$$

where the parameter c depends on the radio platform.

The considered WSN operates as follows: One or multiple nodes of N mobile nodes act as source nodes, and the

* Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan (corresponding author N. Shigei to provide email: shigei@eee.kagoshima-u.ac.jp)

† email: k0830177@kadai.jp

‡ email: miya@eee.kagoshima-u.ac.jp

§ Faculty of Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima 890-0065, Japan,
email: saloko215@gmail.com)

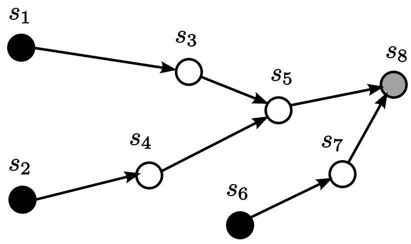


Fig. 1. An example of directed tree for multiple data flows: source (leaf) nodes are s_1, s_2 and s_6, sink node is s_8, $S(s_5) = \{s_3, s_4\}$, and $D(s_5) = \{s_1, s_2\}$.

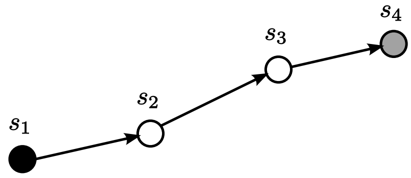


Fig. 2. An example of directed tree for single data flow: s_1 is the source (leaf) node and s_4 is the sink (root) node.

source nodes send their sensing date to a sink node. The sensing data is transferred through one or multiple hops. Whether it uses direct or multi-hop transmission depends on their transmission costs. For example, let the distances between source and sink, source and relay, and sink and relay be denoted by d_1, d_2 and d_3, respectively. If the direct transmission cost of $E_{\rm T}(d_1, m)$ is larger than the multi-hop one of $E_{\rm T}(d_2, m) + E_{\rm T}(d_3, m)$, then the multi-hop transmission via the relay node is used.

III. Mobile Relay

In the model described above, intermediate nodes on the transmission path from a source to the sink can move to reduce the energy consumption in wireless transmission. Therefore, the transmission cost is the sum of the energy consumption by movement and wireless transmission. In [8], the problem for minimizing the transmission cost is formulated as follows. Let $S = (s_1, \cdots, s_N)$ be the list of N nodes in the network. Let o_i be the initial position of node s_i for $1 \le i \le N$ and $O = (o_1, \cdots, o_N)$ be its list. Let $S_{\rm src}$ be the subset of S representing the source nodes. Let $s_{\rm snk}$ be the single sink in S. Let E be the set of directed arcs (s_i, s_j) in the directed tree in which each source node is a leaf and the sink node is the root. An example of the directed tree is shown in Fig.1. Let m_i be the total number of bits to be transmitted by node s_i for $1 \le i \le N$. Let u_i be the position of node s_i for $1 \le i \le N$ and $U = (u_1, \cdots, u_N)$ be its list. The transmission cost for a formation U is given by the following equation.

$$c(U) = \sum_{(s_i,s_j)\in E} a \cdot m_i + b||u_i - u_j||^2 m_i + k||o_i - u_i|| \quad (4)$$

Given instances of S, O, $S_{\rm src}$, $s_{\rm snk}$ and E, then the problem is to determine the mobile node formation U so as to minimize the transmission cost $C(U)$.

An optimal solution for the problem can be determined by an iterative algorithm. Let us explain the algorithm for single data flow case where the number of source nodes is one. Note that the directed tree for single data flow is a path from the source to the root as shown in Fig.2. We assume that $S_{\rm src} = \{s_1\}$, $s_{\rm snk} = s_n$ and the relaying order is s_1, s_2, s_3, $\cdots$. Let $u_i^t = (x_i^t, y_i^t)$ be the position of node s_i after t-th iteration ($t \ge 0$), where $u_i^0 = o_i$. In the iterative algorithm, the updatation of positions alternates between odd number and even number nodes. If t is odd number, for all $1 \le j \le n/2$, each odd-numbered node s_{2j-1} calculates a new position as u_{2j-1}^t and each even-numbered node s_{2j} keeps its position, that is $u_{2j}^t = u_{2j}^{t-1}$. Otherwise, vice versa. As the iteration t increases, the formation of nodes approaches to the optimal one. Note that, at each iteration, the mobile nodes do not actually move and just calculate the positions.

The new position u_i^t of node s_i at t-th iteration is derived from the cost function on the node positions $U^t = (u_1^t, \cdots, u_n^t)$. At t-th iteration, the energy consumption of node s_i is as follows.

$$c_i(U^t) = k||u_i^t - o_i|| + m(a + b||u_{i+1}^t - u_i^t||^2) \quad (5)$$

Since u_{i-1}^t and u_{i+1}^t are fixed, the cost function for determining the optimal position u_i^t is as follows.

$$C_i(U^t) = c_i(U^t) + m(a + b||u_i^t - u_{i-1}^t||^2) \quad (6)$$

The optimal position is obtained by solving the equations $\frac{\partial C_i(U^t)}{\partial x_i^t} = 0$ and $\frac{\partial C_i(U^t)}{\partial y_i^t} = 0$ as follows. When $x_{i-1}^t + x_{i+1}^t \ge 2x_i^t$,

$$x_i^t = \frac{1}{2}(x_{i-1}^t + x_{i+1}^t) - Y_i^t, \quad (7)$$

where

$$Y_i^t = \frac{k}{4b \cdot m} \cdot \frac{1}{\sqrt{1 + \frac{(y_{i-1}^t + y_{i+1}^t - 2q_i)^2}{(x_{i-1}^t + x_{i+1}^t - 2p_i)^2}}} \quad (8)$$

Otherwise,

$$x_i^t = \frac{1}{2}(x_{i-1}^t + x_{i+1}^t) + Y_i^t. \quad (9)$$

For any case,

$$y_i^t = \frac{y_{i-1}^t + y_{i+1}^t - 2q_i}{x_{i-1}^t + x_{i+1}^t - 2p_i}(x_i^t - p_i) + q_i. \quad (10)$$

Since the above calculations for s_i do not need any information on other nodes than itself s_i and its neighboring nodes s_{i-1}, s_{i+1}, the iterative algorithm can be decentrally performed by each individual node with information exchange between neighboring nodes.

The number of iterations needed for convergence to the optimal position depends on the initial formation and the used parameters such as m, a, b and k. However, for most typical cases, the number of iterations around 10 provides a good convergence. Fig.3 is an example of the position change at each iteration for a typical setting.

The algorithm can be extended to the case of multiple data flows where the number of source nodes is more than one. An example of the directed tree for this case is shown in Fig.1. Let $S(s_i)$ be the set of S_i's child nodes in the directed tree. Let $D(s_i)$ be the set of nodes that are leafs and s_i's grandchildren. Let D_i be the number of nodes in $D(s_i)$. For a given node s_i, let s_d be the node that is the

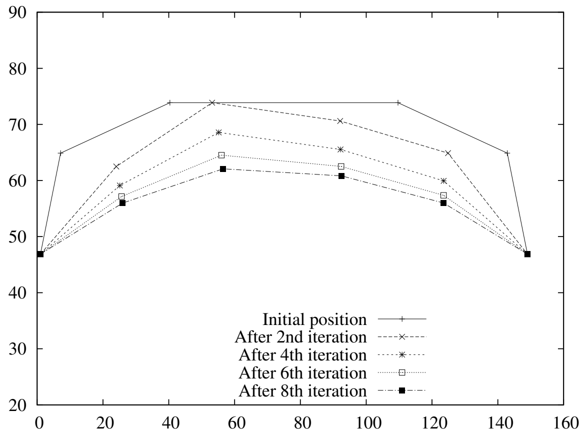


Fig. 3. An example of the position change at each iteration for $m = 40$MB, $k = 2.0$ J/m, $a = 0.6 \times 10^{-7}$ J/bit and $b = 4.0 \times 10^{-10}$ Jm^{-2}/bit.

parent node of s_i in the directed tree. Then the cost function is as follows.

$$C_i(U^t) = k\|u_i^t - o_i\| + D_i m(a + b\|u_d^t - u_i^t\|^2) + \sum_{s_l \in S(s_i)} D_l m(a + b\|u_i^t - u_l^t\|^2) \quad (11)$$

The optimal position can be obtained by solving the equations $\frac{\partial C_i(U^t)}{\partial x_i^t} = 0$ and $\frac{\partial C_i(U^t)}{\partial y_i^t} = 0$.

IV. Battery-Aware Mobile Relay

In this section, we present battery-aware algorithms for mobile relay[10]. The aim of the proposed approach is to maximize the network lifetime defined as the time where all the nodes are alive. This approach has the following advantages: 1) The path reconfiguration needed in the case of node down on the transmission path can be avoidable as much as possible, and 2) the coverage of sensing area by mobile nodes can be kept high. The proposed algorithms determine the node configuration such that a relay node with lower remaining energy consumes less energy and a relay node with higher remaining energy supports lower energy nodes by consuming more energy.

A. Battery-Aware Mobile Relay for Single Data Flow

In this subsection, we explain the algorithm for single data flow case where the number of source nodes is one, that is $S_{\text{src}} = \{s_1\}$ and $s_{\text{snk}} = s_n$. We assume that the relay order is s_1, s_2, s_3, $\cdots$. Let e_i be the battery energy level of node s_i. The proposed cost function is as follows:

$$C_i(U^t) = \frac{k||u_i^t - o_i||}{e_i} + \frac{m(a + b||u_{i+1}^t - u_i^t||^2)}{e_i} + \frac{m(a + b||u_i^t - u_{i-1}^t||^2)}{e_{i-1}}. \quad (12)$$

As e_i decreases, the first and second terms in the cost function keep the movement and transmission ranges of node s_i smaller. As e_{i-1} decreases, the third term encourages node s_i to offer more assistance to node s_{i-1}. The optimal position is obtained by solving the equations $\frac{\partial C_i(U^t)}{\partial x_i^t} = 0$ and $\frac{\partial C_i(U^t)}{\partial y_i^t} = 0$ as described in Section III. When $x_{i-1}^t + x_{i+1}^t \geq 2x_i^t$,

$$x_i^t = \frac{e_i x_{i-1}^t + e_{i-1} x_{i+1}^t}{e_i + e_{i-1}} - Y_i^t, \quad (13)$$

where

$$Y_i^t = \frac{e_{i-1} k}{2bm(e_i + e_{i+1})} \cdot \frac{1}{\sqrt{1 + \frac{(e_i(y_{i-1}^t - q_i) + e_{i-1}(y_{i+1}^t - q_i))^2}{(e_i(x_{i-1}^t - p_i) + e_{i-1}(x_{i+1}^t - p_i))^2}}}. \quad (14)$$

Otherwise,

$$x_i^t = \frac{e_i x_{i-1}^t + e_{i-1} x_{i+1}^t}{e_i + e_{i-1}} + Y_i^t. \quad (15)$$

For any case,

$$y_i^t = \frac{e_i(y_{i-1}^t - q_i) + e_{i-1}(y_{i+1}^t - q_i)}{e_i(x_{i-1}^t - p_i) + e_{i-1}(x_{i+1}^t - p_i)}(x_i^t - p_i) + q_i. \quad (16)$$

The above calculations for s_i, as well as (7)∼(10), do not need any information on other nodes than itself s_i and its neighboring nodes s_{i-1} and s_{i+1}. Therefore, its iterative algorithm can be also decentrally performed by each individual node with information exchange between neighboring nodes.

B. Battery-Aware Mobile Relay for Multiple Data Flows

In this subsection, we extend the proposed algorithm to the case of multiple data flows. Let $S(s_i)$ be the set of nodes that send the data directly to s_i on the data flows. Let $D(s_i)$ be the set of source nodes whose transmitting data is relayed by node s_i. Let D_i be the number of nodes in $D(s_i)$. For a given node s_i, let s_d be the node that is the parent node of s_i in the directed tree. Then the cost function is as follows.

$$C_i(U^t) = \frac{k\|u_i^t - o_i\|}{e_i} + \frac{D_i m(a + b\|u_d^t - u_i^t\|^2)}{e_i} + \sum_{s_l \in S(s_i)} \frac{D_l m(a + b\|u_i^t - u_l^t\|^2)}{e_l} \quad (17)$$

The optimal position is also obtained by solving the equations $\frac{\partial C_i(U^t)}{\partial x_i^t} = 0$ and $\frac{\partial C_i(U^t)}{\partial y_i^t} = 0$. When $x_{i-1}^t + x_{i+1}^t \geq 2x_i^t$,

$$x_i^t = \frac{D_i x_d^t + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l} x_l^t}{D_i + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}} - Y_i^t, \quad (18)$$

where

$$Y_i^t = \frac{k}{2bm\left(D_i + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}\right)} \times \left(1 + \left(\frac{D_i(y_d^t - q_i) + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}(y_l^t - q_i)}{D_i(x_d^t - p_i) + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}(x_l^t - p_i)}\right)^2\right)^{-1/2}. \quad (19)$$

Otherwise,

$$x_i^t = \frac{D_i x_d^t + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l} x_l^t}{D_i + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}} + Y_i^t. \quad (20)$$

For any case,

$$y_i^t = \frac{D_i(y_d^t - q_i) + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}(y_l^t - q_i)}{D_i(x_d^t - p_i) + e_i \sum_{s_l \in S(s_i)} \frac{D_l}{e_l}(x_l^t - p_i)}(x_i^t - p_i) + q_i. \quad (21)$$

The iterative algorithm with the above equations can be also decentrally performed by each individual node with information exchange between neighboring nodes.

V. Battery-Aware Initial Route Construction

Mobile relay needs to be given initial routes, each of which describes the sequence of nodes used for relaying the data from a source to the sink. If the objective is to minimize the communication cost, it is desirable to employ an optimal solution method such as Dijkstra's algorithm. However, Dijkstra's algorithm has difficulty when it is implemented on the network. The algorithm needs information over broad area of the network at each step of the calculation, and this requires global information on the network or frequent information exchanges among nodes. Therefore, from the viewpoint of implementation, we consider to determine the initial route in a greedy fashion.

In this paper, the following greedy algorithm, which does not take into account node's battery level, is employed as a conventional method. The conventional algorithm starts with each source node and, for each intermediate node, it selects the nearest node to the sink among the neighboring nodes as the next node. Each step of the algorithm is formalized as follows. Let $s_{\rm cur}$ be the current node. Let $N(s)$ be the set of neighboring nodes of node s. Let $s_{\rm snk}$ be the sink node. Then the next node $s_{\rm next} \in N(s)$ is selected such that

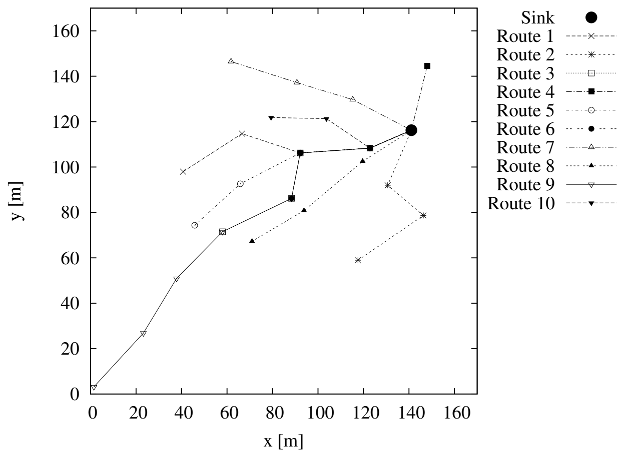
$$d(s_{\rm next}, s_{\rm snk}) = \min_{s_l \in N(s_{\rm cur})} d(s_l, s_{\rm snk}). \quad (22)$$

Fig.4.(a) shows an initial route constructed by the conventional greedy algorithm for 10 source nodes.

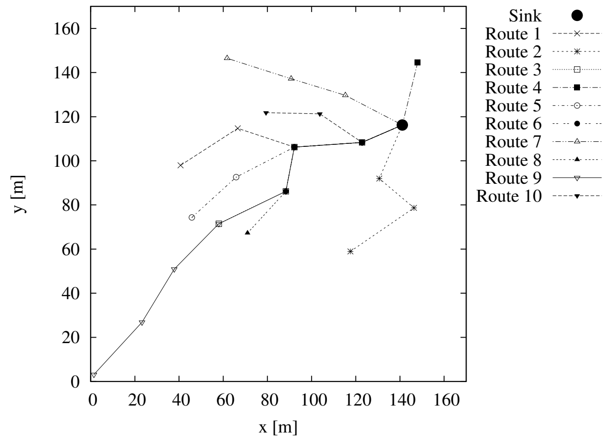
The conventional greedy algorithm determines the initial route according to only the distance to the sink node. When the battery levels are not uniform for all nodes, selecting a node with low battery level will shorten the network lifetime. Obviously, nodes with low battery levels should be excluded from the initial route. Therefore, we incorporate node's battery levels into the selection rule for the next node. Our proposed greedy algorithm BRC (Battery-aware Route Construction) selects the next node $s_{\rm next} \in N(s)$ such that

$$\frac{d(s_{\rm next}, s_{\rm snk})}{e_{\rm next}^{\alpha}} = \min_{s_l \in N(s_{\rm cur})} \frac{d(s_l, s_{\rm snk})}{e_l^{\alpha}}, \quad (23)$$

where $e_{\rm next}$ and e_l are battery levels of nodes $s_{\rm next}$ and s_l respectively, and $\alpha \leq 1.0$ is the parameter controlling the balance between distance and battery level. When using very large α, the route construction tends to fail. Because a further node than the current node may be frequently selected. As α approaches to 0, the selection becomes the same as the conventional method. Therefore, we have to find a moderate value for α. The moderate value depends on the battery levels, the number of sources, the number of nodes, the field size, etc. However, the determination is comparatively easy. Starting from a large value, until succeeding the route construction, we may try the route construction with a smaller value. In our simulations, logarithmic decrement of α was sufficient for obtaining a good performance. Therefore, in general case, we may retry the route construction several times.



(a) For conventional greedy algorithm.



(b) For greedy algorithm BRC.

Fig. 4. Initial route examples for 10 source nodes.

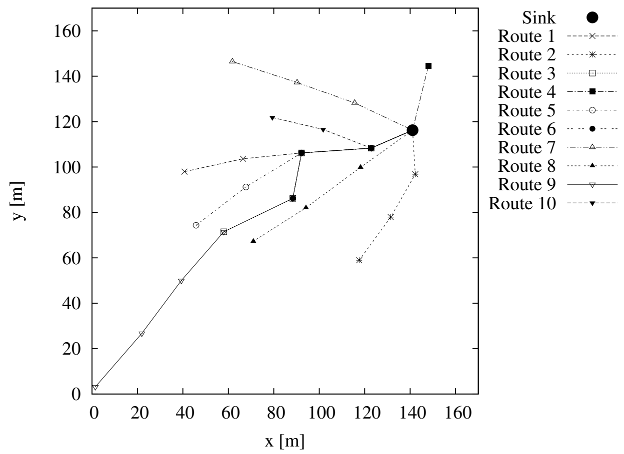
Fig.4.(b) shows an initial route constructed by the proposed algorithm BRC for 10 source nodes. In the configuration, we can observe the different selection for Route 8.

VI. Numerical Simulation

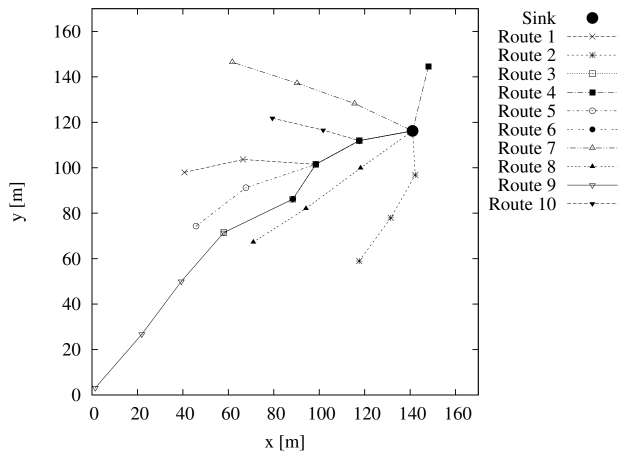
In order to the effectiveness of the proposed methods, we perform numerical simulations. In the simulation, N mobile sensor nodes are initially randomly distributed in a 150m $\times$ 150 square field. From the N nodes, 10 $\sim$ 30 source nodes and one sink node are randomly selected. The parameter setting used for energy model is as follows: $k = 2$ J/m, $a = 0.6 \times 10^{-7}$ J/bit, $b = 4.0 \times 10^{-10}$ Jm^{-2}/bit and $c = 1.4 \times 10^{-7}$ J/m. The maximum range of wireless communication is set to 35 m. These parameters are same as those used in [9]. Further, in the simulation, the batteries of mobile nodes except for sink node are initially randomly charged in the range of 10 kJ$\sim$150 kJ. We assume that the sink node uses an unlimited energy source.

We evaluate the following four types of MR (Mobile Relay configuration) methods.

- **MR for Single data flow (MRS)** renews only the positions of the nodes having just one child node in

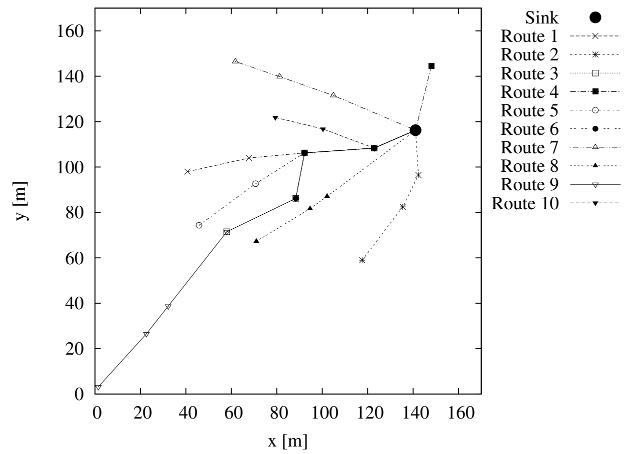


(a) The configuration obtained by MRS.

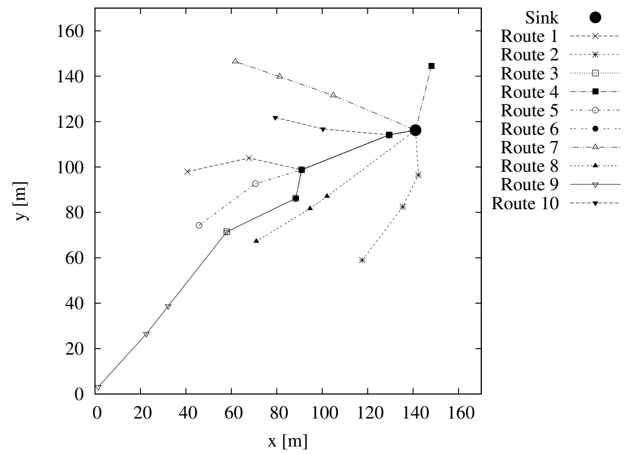


(b) The configuration obtained by MRM.

Fig. 5. The configurations obtained by the conventional methods MRS and MRM for an initial configuration shown in Fig.4



(a) The configuration obtained by BMRS.



(b) The configuration obtained by BMRM.

Fig. 6. The configurations obtained by the proposed methods BMRS and BMRM for an initial configuration shown in Fig.4

the directed tree by using (7), (8), (9) and (10), and it does not change the initial positions for the nodes having more than one child nodes.

- **MR for Multiple data flows (MRM)** renews the positions of the nodes having more than one child node in the directed tree by using the equations based on (11), and it also renews the other nodes by using (7), (8), (9) and (10).
- **Battery-aware MR for Single data flow (BMRS)** renews the positions of the nodes having just one child node in the directed tree by using (13), (14), (15) and (16), and it does not change the initial positions for the nodes having more than one child nodes.
- **Battery-aware MR for Multiple data flow (BMRM)** renews the positions of the nodes having more than one child node in the directed tree by using (18), (19), (20) and (21), and it also renews the other nodes by using (13), (14), (15) and (16).

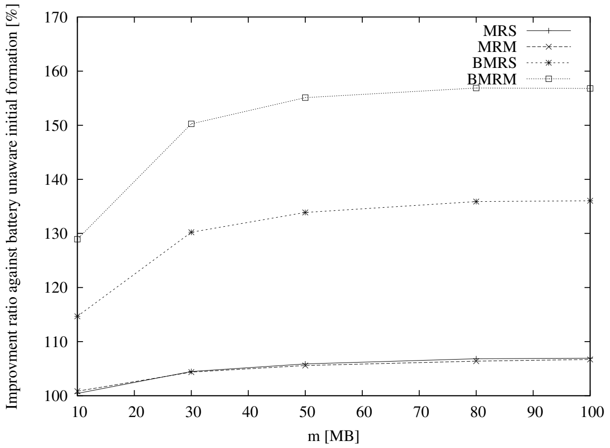
In the first half of the simulation, we employ the conventional greedy algorithm for initial route construction. Figures 5 and 6 show the configurations obtained by MRS, MRM, BMRS and BMRM for the initial configuration shown in Fig.4.(a). From the result, we can observe the following tendencies.

- For MRS and MRM (Figs. 5.(a) and 5.(b)), the lengths of edges are almost same in each of paths that are subgraph of the directed tree and whose internal node have just one child and one parent.
- The paths for MRM are straight compared with the ones for MRS. This is because the nodes having more than one child move toward their optimal positions.
- For BMRS and BMRM (Figs. 6.(a) and 6.(b)), the paths become near straight compared with the original formation. However, the length of edges are obviously different. This is because the child node of a short edge has less remaining energy.
- BMRM provides more shorter paths than BMRS, because the nodes having more than one child move toward their optimal positions.

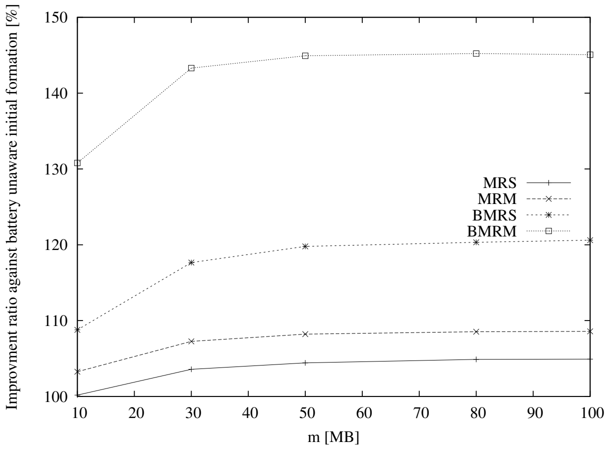
Next, the methods are evaluated in terms of the amount of data that the source node collects until any node goes down due to battery dead. The simulation results for the numbers of source nodes 10, 20 and 30 are shown in Fig.7. The improvement ratio is defined as follows:

$$\frac{B}{A} \times 100 \quad [\%], \tag{24}$$

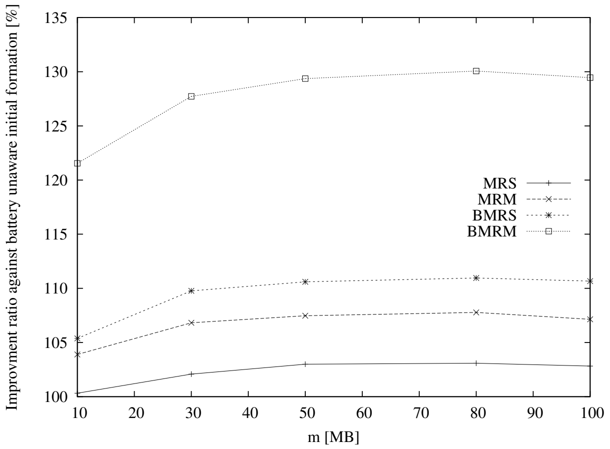
where B is the amount of data collected for each of the methods and A is the amount of data collected for the initial



(a) For 10 source nodes.



(b) For 20 source nodes.



(c) For 30 source nodes.

Fig. 7. The chunk size of data versus the improvement ration of the data collection capacity with the conventional greedy initial route configuration.

node formation. Note that all the initial route configuration is obtained by the conventional greedy algorithm. The results are average values for 100 instances of the network model.

From the results shown in Fig.7, we can observe the following tendencies.

(1) When the chunk size is more than about 30MB, all the methods provides constant improvement.
(2) The methods moving the all node positions such as MRM and BMRM are more effective than the methods only moving the nodes on single data flow such as MRS and BMRS.
(3) As the number of source nodes increases, our battery-aware approach such as BMRS and BMRM becomes more effective than the conventional approach such as MRS and MRM. Especially, the advantage of BMRM against MRS and MRM becomes larger with the number of source nodes.

For every methods, the chunk size m should set to the amount of data that actually are transferred. However, it is difficult to know the actual one, because it depends on the remaining energy levels on every nodes on the paths. The tendency (1) shows that we can receive benefits of the proposed methods by setting the chunk size larger than some value.

From here, we evaluate the performance of the proposed battery-aware route construction algorithm BRC. For all the simulation, we use the parameter setting $\alpha = 0.05$ for 10 sources and $\alpha = 0.01$ for 20 and 30 sources. Fig.8 shows the improvement ratio for each of MR methods with BRC, where the improvement ratio is defined as follows:

$$\frac{B'}{A} \times 100 \quad [\%], \tag{25}$$

where B' is the amount of data collected for each of the methods with BRC and A is the amount of data collected for the initial node formation obtained by the conventional greedy algorithm. For "Initial" in Fig.8, B' is the amount of data collected for the initial node formation obtained by BRC.

From the results shown in Fig.8, we can observe the following tendencies.

(1) For every methods, the improvement ratio is better than the one with the conventional route construction shown in Fig.7.
(2) From the result for Initial, for any chunk size, BRC achieves constant improvement ratios 118%, 105%, 106% for 10, 20 and 30 sources, respectively.
(3) BMRS receives the most benefit from BRC, because the differences between BMRS and BMRM become smaller.

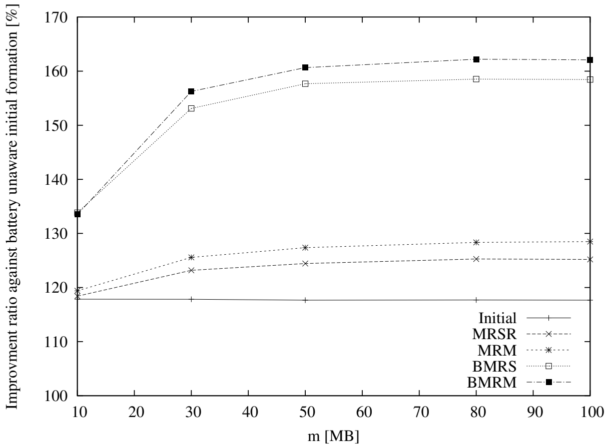
Next, we examine how much BRC can improve the performance for each MR method. The results are shown in Fig.9, where the improvement ratio is defined as follows:

$$\frac{B'}{B} \times 100 \quad [\%], \tag{26}$$

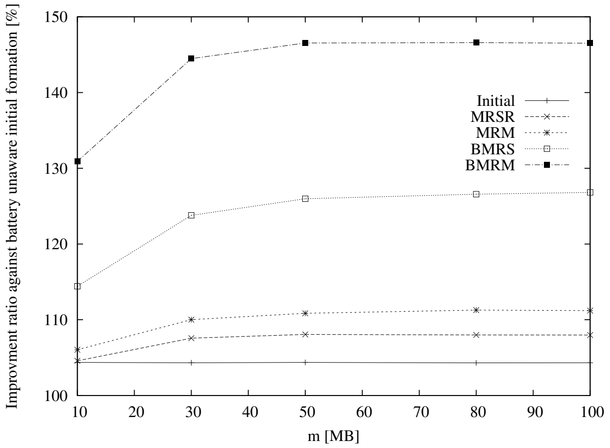
where B' is the amount of data collected for each MR method with BRC and B is the amount of data collected for each MR method with the conventional initial route construction.

From the results shown in Fig.9, we can observe the following tendencies.

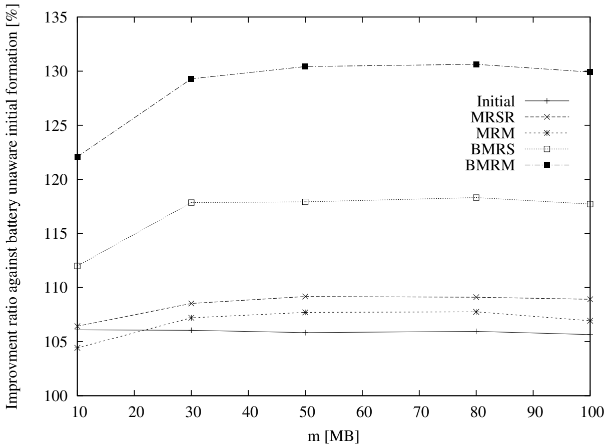
(1) For BMRS, BRC achieves the best or a good improvement ratio for any number of sources.
(2) For MRM, BRC achieves the best improvement for small number of source nodes, 10 sources. However, as the number of sources increases, the improvement ratio rapidly decreases.
(3) For BMRM, BRC's improvement ratio is not high for any number of sources. Since BMRM achieves



(a) For 10 source nodes.

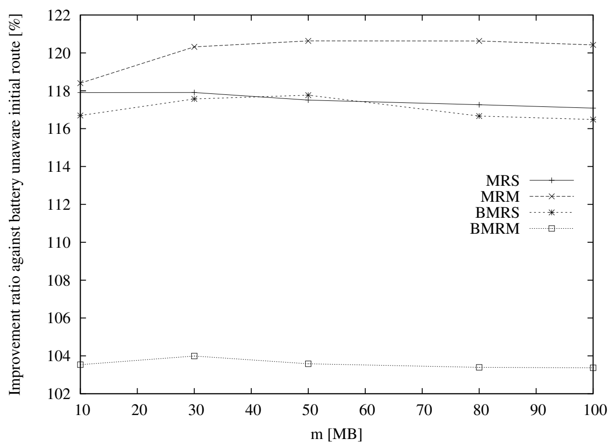


(b) For 20 source nodes.

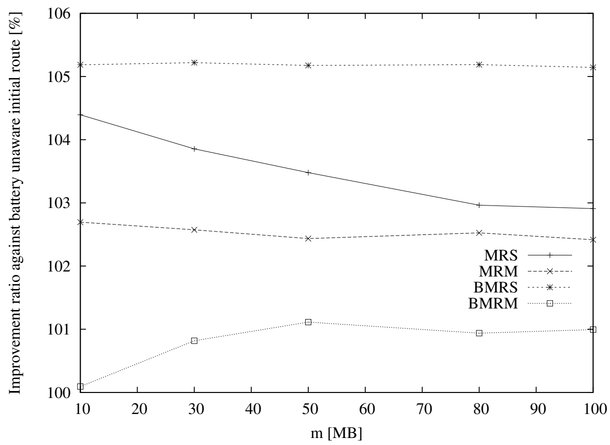


(c) For 30 source nodes.

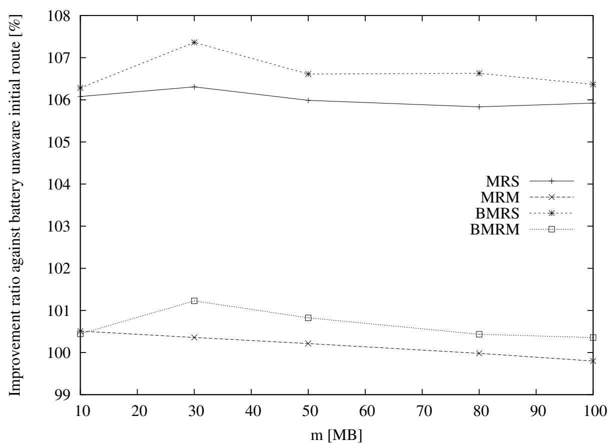
Fig. 8. The chunk size of data versus the improvement ration of the data collection capacity for the combination of BRC and each MR method.



(a) For 10 source nodes.



(b) For 20 source nodes.



(c) For 30 source nodes.

Fig. 9. The improvement ration of the data collection capacity by BRC for each MR method.

always the highest improvement ratio among all the MR methods, in other words, BMRM can achieves good performance for any initial route configuration.

The simulation results shows that BRC can enhances the performance for most cases.

VII. Conclusion

In this paper, we presented battery-aware algorithms for mobile relay and initial route construction. All the presented algorithms take into account node's battery levels. For mobile relay, given a sequence of relaying nodes, our algorithms determine the movement of relaying nodes according to not only the total cost of movement and communication but also their battery levels[10]. BMRS and BMRM treat single data flow and multiple data flows, respectively. The simulation results show that BMRM is the most effective.

Further, in this paper, we proposed battery-aware algorithm for initial route construction. Initial route construction is needed for determining the sequence of relaying nodes, which is provided to mobile relay algorithms. The proposed BRC avoids using nodes with low battery levels according to not only their communication costs but also their battery levels. In the simulation, BRC is applied to four types of MR methods. The simulation results show that, for most cases, BRC enhances the performance in terms of network lifetime. In future works, we will consider the refinement of BRC.

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