Multiple Route Construction with Path-overlap Avoidance for Mobile Relay on WSN

Yogi AnggunSaloko Yudo[1], Noritaka Shigei[2], and Hiromi Miyajima[3]

***Abstract*—Low energy consumption is very important in WSN (Wireless Sensor Network), since sensor nodes are powered by limited power batteries. In recent years, mobile relay has been studied in order to save the energy consumption on WSN. Initial route construction is needed for mobile relay to determine the sequence of relaying nodes. Battery-Aware Initial Route construction by Dijkstra's Algorithm (BAIR-D) has been proposed. BAIR-D employs a Dijkstra's algorithm and takes into account node's battery level into the cost function to find the initial route. However, when applying it to multiple sources, the constructed paths are necessarily overlapped with high probability. Therefore, it increases the energy consumption of the nodes on overlapped paths. In this study, we propose battery-aware multiple route construction with path-overlap avoidance, which is referred as BMRC-POA. Unlike BAIR-D, BMRC-POA avoids path-overlap in multiple route construction for mobile relay. There are two steps for determining the initial route in BMRC-POA. First, the initial route construction for every source node is determined without path-overlap. Second, if the route construction for some sources failed, then path-overlap is allowed. In [12], we did not take into account the order of source nodes in route construction and we used the random order of source nodes in the simulation. In this paper, we consider three types of orders of source nodes in route construction. In addition to the random order, the rest two orders are determined based on the distance from source nodes to the sink. In the simulation results, we show that BMRC-POA outperforms BAIR-D in terms of the network lifetime. Further, we show the effective routing order for BMRC-POA.**

***Index Terms*—Dijkstra's algorithm, mobile node, initial route, multi-hop communication, overlapping of multiple paths, wireless sensor network**

I. Introduction

ENERGY is the most important resource in Wireless Sensor Network (WSN) [1], because it determines the lifetime of a sensor node. Since the sensor nodes are usually powered by limited power batteries, low energy consumption is very important, in order to prolong the network lifetime of WSN. In recent years, many researchers designed and developed techniques for prolonging the network lifetime of WSN [1,2]. One of the techniques is mobile relay [3,4,5]. The concept of mobile relay is that some movable nodes change their location so as to minimize the total energy consumed by both wireless transmission and locomotion. Mobile relay needs to determine an initial route, which describes the sequence of nodes used for relaying the data from a source node to a sink node, and then the relaying nodes change their location so as to reduce their energy consumption.

In previous studies, we have already proposed Battery-Aware Initial Route Construction-Dijkstra's algorithm (BAIR-D) for determining the initial route based on Dijkstra's algorithm [6]. This method can construct the optimal path in terms of given cost function. Further, the algorithm takes into account nodes' battery levels and avoids using nodes with low battery levels. However, when applying it to multiple sources, a problem arises. Since BAIR-D constructs the optimal path for each source, the constructed paths are necessarily overlapped with a high probability. The path-overlap increases the energy consumption of the nodes on overlapped paths. This makes the overloaded nodes go quickly down.

In this study, we propose battery-aware multiple route construction with path-overlap avoidance (BMRC-POA). To overcome the problem in the conventional method, BMRC-POA finds the initial route for mobile relay with path-overlap avoidance. It avoids some nodes to be a relaying node for multiple source nodes. It also avoids the source node to be a relaying node to another source node. Avoiding path-overlap in multiple route construction can save the energy for some sensor nodes. Therefore, it can prolong the lifetime of sensor nodes. This method consists of two steps. First, the initial route construction for every source node is determined without path-overlap. Second, if some source nodes have no route, then the initial route construction is performed with a path-overlap scenario. In [12], we did not take into account the order of source nodes in route construction and we used the random order of source nodes in the simulation. In this paper, we consider three types of orders of source nodes in route construction. In addition to the random order, the rest two orders, nearest-first order and farthest-first order, are determined based on the distance from source nodes to the sink. We compare BMRC-POA and BAIR-D in terms of the number of operating rounds, the successful rate of initial route construction and the total cost. Further, we compare three types of orders for BMRC-POA. In the simulation results, we show that BMRC-POA outperforms BAIR-D in terms of the network lifetime. Further, we show that the farthest - first order is the most effective routing order for BMRC-POA compared with random order and nearest-first order.

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II. MOBILE WSN

A. Mobile WSN Model

The WSN model considered in this study consists of N mobile nodes and one sink node. The mobile nodes can estimate their own location by an equipped GPS unit or other systems. Moreover, they can move by using equipped electric motors. We adopt the same energy consumption model as in [3]. The energy $E_M(d)$ is consumed when a mobile node moves through a distance d [m]:

$$E_M(d) = k \cdot d \qquad [\mathrm{J}], \tag{1}$$

where the parameter k [J/m] depends on the moving velocity. The energy $E_T(d,m)$ is consumed when a node transmits a data of *m* [bit] over a distance of *d* [m]:

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

where the parameters a and b depend on the environment. The energy $E_R(m)$ is consumed when a node receives a data of *m* [bit]:

$$E_R(m) = c \cdot m \qquad [\mathrm{J}], \tag{3}$$

where the parameter *c* depends on the radio platform.

B. Mobile Relay

The mobile relay algorithms consist of two steps. The first step is to determine the initial route and the second step is to calculate the optimal position. Initial route construction in the first step is needed for determining the sequence of relaying nodes, which is provided to mobile relay algorithms. In the second step, the mobile relay algorithm calculates the location of intermediate nodes on the transmission path from the source to the sink so as to minimize a given cost function such as the total energy consumption of movement and transmission. Fig.1 shows an example of node movement. After the step two, the data outgoing from the source is relayed to the sink.

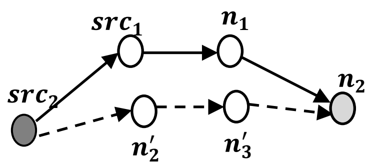


Fig. 1. An example of node movement in mobile relay: $n_1$acts as a source node, n_4 acts as a sink node. n_2 and n_3 act as intermediate nodes. n_2' and n_3' show the optimal positions of n_2 and n_3, respectively.

For the step two, several types of mobile relay algorithms have been proposed. The algorithms determine the optimal positions of relaying nodes in terms of a given objective function. In [3], the objective function is the total cost of movement and communication. In [5], the objective function takes into account not only the total cost but also nodes' battery levels. The latter one can save the energy consumption on nodes with low battery levels, and it is advantageous to prolonging the network lifetime. Therefore, in this paper, we use the latter one, battery-aware mobile relay algorithm.

III. CONVENTIONAL 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 [4]. In the conventional methods [6], each node selects specific nodes to be the relaying nodes to relay data according to some criteria in order to prolong the network lifetime of WSN.

The works in [5,6] proposed some initial route construction algorithms. The objective of the algorithms was to minimize the total energy consumed by both wireless transmission and locomotion. In the works, we have adopted greedy algorithm to determine the initial routes. In the conventional greedy algorithm, the energy consumption is proportional to the square of distance. The weight of a node n_{a} to a node $n_{\mathrm{b}}$is as follows:

$$w(n_{\mathrm{a}}, n_{\mathrm{b}}) = d(n_{\mathrm{a}}, n_{\mathrm{b}})^2, \tag{4}$$

where $d(n_{\mathrm{a}}, n_{\mathrm{b}})$ is the distance between node n_{a} to node n_{b}.

The greedy algorithm in [5] has determined the initial route according to only the distance to the sink. When the battery levels are not uniform for all nodes, selecting a node with low battery level will shorten the network lifetime. Therefore, we incorporated node's battery levels into the cost function as in [6]. The weight of a node n_{a} to a node n_{b} is calculated by the following equation,

$$w(n_{\mathrm{a}}, n_{\mathrm{b}}) = \frac{d(n_{\mathrm{a}}, n_{\mathrm{b}})^2}{e_{\mathrm{b}}^{\alpha}}, \tag{5}$$

where e_{b} is the battery level of node n_{b}, and $\alpha > 0$ is the parameter controlling the balance between distance and battery level. When using larger α, a node with higher battery level tends to be selected as a relaying node. When using smaller α, a node with lower communication cost to be selected as a relaying node. Therefore, we have to find an effective value for α. The effective value of α depends on the battery level, the number of sources, the number of nodes, the field size, etc.

In the following, the conventional route construction methods are introduced [5,6].

A. Route Construction Based on Greedy Approach

Starting with the source node, the route construction extends the relaying path to the sink node step by step. At each step, the extension of the path is determined in a greedy fashion by using the local information on the front line node. Let n_{cur} be the current node that is the front line of the path extension. The next front line node n_{nxt} is determined as follows:

$$d(n_{\mathrm{nxt}}, n_{\mathrm{snk}}) = \min_{n \in \mathrm{N}(n_{\mathrm{cur}})} d(n, n_{\mathrm{snk}}), \tag{6}$$

The algorithm requires only the number of communications, proportional to the relaying nodes. Therefore, it can be easily implemented in a distributed fashion.

Algorithm BAIR-D($\mathrm{N_{all}}, n_{\mathrm{src}}, n_{\mathrm{snk}}, w, \mathrm{N}$)

/* Inputs */
$\mathrm{N_{all}}$: The set of all the nodes
n_{src}: Source node
n_{snk}: Sink node
$w(n', n")$ for all $n', n" \in \mathrm{N_{all}}$:
    the cost of edge $(n', n")$
$\mathrm{N}(n)$ for all $n \in \mathrm{N_{all}}$:
    the set of the nodes within the direct communication range of node n
/* Output */
R: the set of the edges of the route

begin
  /* Initializations */
  /* The sets of member nodes and selected edges are empty. */
  $\mathrm{M} \leftarrow \emptyset$;
  $\mathrm{E} \leftarrow \emptyset$;
  /* Starting from the sink node */
  $\mathrm{M} \leftarrow \{n_{\mathrm{snk}}\}$;
  $W(n_{\mathrm{snk}}) \leftarrow 0$;

  /* Main loop */
  do
    /* Find the non-member node with the minimum cost from the sink node. */
    Find $n_{\mathrm{mem}} \in \mathrm{M}$ and $n_{\mathrm{non}} \in \mathrm{N_{all}} \setminus \mathrm{M}$ s.t.
    $n_{\mathrm{non}} \in \mathrm{N}(n_{\mathrm{mem}})$ and $W(n_{\mathrm{mem}}) + w(n_{\mathrm{mem}}, n_{non}) = \min_{n' \in \mathrm{M}, n" \in \mathrm{N_{all}} \setminus \mathrm{M}} (W(n') + w(n', n"))$;

    /* Add the non-member to members. */
    $\mathrm{M} \leftarrow \mathrm{M} \cup \{n_{\mathrm{non}}\}$;

    /* Add the edge to ones for the candidate routes. */
    $\mathrm{E} \leftarrow \mathrm{E} \cup \{(n_{\mathrm{mem}}, n_{\mathrm{non}})\}$;

    /* Update the cost. */
    $W(n_{\mathrm{non}}) \leftarrow W(n_{\mathrm{mem}}) + w(n_{\mathrm{mem}}, n_{\mathrm{non}})$;
  until $n_{\mathrm{src}} \in \mathrm{M}$;

  /* Extract the route from the source to the sink */
  $\mathrm{R} \leftarrow \emptyset$;
  $n_{\mathrm{cur}} \leftarrow n_{\mathrm{src}}$;
  while $n_{\mathrm{cur}} \neq n_{\mathrm{snk}}$ do
    Select $(n_{\mathrm{nxt}}, n_{\mathrm{cur}}) \in \mathrm{M}$;
    $\mathrm{R} \leftarrow \mathrm{R} \cup \{(n_{\mathrm{nxt}}, n_{\mathrm{cur}})\}$;
    $n_{\mathrm{cur}} \leftarrow n_{\mathrm{nxt}}$;
  end of while

end.

Fig. 2. BAIR-D Algorithm

B. Battery-Aware Initial Route Construction by Dijkstra's Algorithm (BAIR-D)

The drawback of the greedy route construction is that the optimality of the obtained route is not guaranteed. In this subsection, we introduce battery-aware initial route construction based on Dijkstra's algorithm (BAIR-D).

Dijkstra's algorithm is used for finding the shortest path from a node to the other nodes in the network [7]. The algorithm has been applied to the multi hop communication in WSN [8,9]. However, the methods are for fixed nodes and do not take into account node's battery levels. In this method, BAIR-D, Dijkstra's algorithm is used for mobile relay, and node's battery levels are incorporated into the cost function.

The algorithm starts with a sink node for calculating all the possible routes, and at each step it selects the node with the minimum total cost among the non-member of neighboring nodes to the member nodes and adds the selected node into the member nodes. The algorithm is shown in Fig.2.

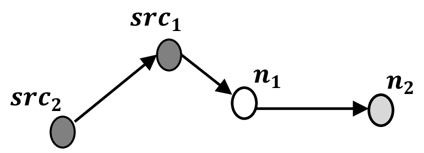
The total cost $W(n_{\mathrm{b}})$ from the sink node to a node n_{b} is calculated by the following equation:

$$W(n_{\mathrm{b}}) = W(n_{\mathrm{a}}) + w(n_{\mathrm{a}}, n_{\mathrm{b}}), \qquad (7)$$

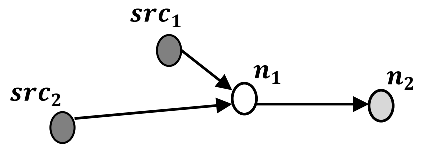
Unlike greedy fashion, the implementation of Dijkstra's algorithm requires global information on the network at each step of the calculation. However, this method determines the initial route for mobile relay by using path-overlap scenario. Some sensor nodes share the path for transmitting the data from source node to the sink node.

IV. Battery-aware Multiple Route Construction with Path-overlap Avoidance

In this section, we propose Battery-aware Multiple Route Construction with Path-Overlap Avoidance (BMRC-POA). The purpose is to reduce the energy consumption of the overloaded nodes on the overlapped path.



3.(a). An example of initial route construction of BAIR-D



3.(b). An example of initial route construction of BMRC-POA

Fig. 3. An example of initial route construction of BAIR-D and BMRC-POA. src_1 acts as a source node 1, src_2 acts as a source node 2. n_1 acts as intermediate node and n_2 acts as sink node.

Unlike BAIR-D, BMRC-POA avoids the path-overlap as much as possible in the route construction. The path-overlap increases the energy consumption of the nodes on overlapped paths. This makes the overloaded nodes go quickly down.

```
Algorithm BMRC-POA(N_all, N_src, n_snk, w, N)

/* Inputs */
N_all: the set of all the nodes
N_src: the set of source nodes

n_snk: Sink node
w(n',n")for all n',n" ∈ N_all:
                    the cost of edge (n',n")
N(n)for all n ∈ N_all:
    the set of the nodes within the
    direct communication range of node n

/* Output */
R(n)for all n ∈ N_src: the set of edges of route
     for source n

begin

   N_av ← N_all;
   for each n_src of N_src do
      /* Find route of n_src without
       overlapping */
      (A) BAIR − D(N_av, n_src, n_snk, w, N);

      if R(n_src) is no route then

         /* Find route of n_src with
         overlapping */
         (B) BAIR − D(N_all, n_src, n_snk, w, N);

         if R(n_src) is no route then
            terminate the algorithm as
            failed construction;
         else
            // Update available node set
            Let N_used be the set of used
            nodes in (B);
            N_av ← N_all\N_used;
         end if

      else
         /* Update available node set */
         Let N_used be the set of used nodes
         in (A);
         N_av ← N_av\N_used;
      end if

   end for
end.
```

Fig. 4. BMRC-POA Algorithm

Further, the algorithm takes into account nodes' battery levels and avoids using nodes with low battery levels. The weight is calculated by eq. (5) and the total cost is calculated by eq. (7).

Fig. 3 shows the difference of initial route constructions between BAIR-D and BMRC-POA. Fig. 3(a) shows that overlapping the source node is allowed in BAIR-D. Source node 1 (src_1) can be used as a member of relaying node for source node 2. On the other hand, in Fig. 3(b), the initial route obtained by BMRC-POA avoids the source node 1 (src_1) to be a member of relaying node for source node 2 (src_2).

Unlike BAIR-D, this algorithm tries to avoid the path-overlap in the route construction. The nodes already used have to be excluded from the available nodes for the next construction paths. Further, if some source nodes cannot find the neighboring nodes to be the next node, then overlapping the path is allowed. All the nodes can be used in order to obtain the successful in route construction. The algorithm is shown in Fig.4.

V. Route Construction Based on The Order of Distance

In route construction with multiple source nodes, the route has to be constructed for each source node. In [12], we did not take into account the order of source nodes in route construction. In the simulations of [12], the route construction for each source node is performed in the order of the source node ID's. Since the node ID's are numbered independently of their coordinates, the order of source nodes in route construction can be regarded as a random order. In this paper, we consider three types of orders of source nodes in route construction. In addition to the random order, the rest two orders, nearest-first order and farthest-first order, are determined based on the distance from source nodes to the sink. For the nearest-first order, the routing order is the nearest source node to the sink, the second nearest one, ... , and the farthest one. For the farthest-first order, the routing order is the farthest source node to the sink, the second farthest one, ... , and the nearest one.

In the simulation, three types of orders of source nodes are evaluated in terms of the number of operating rounds and the successful rate of route construction.

VI. Numerical Simulation

In order to show the effectiveness of the proposed method, we perform numerical simulations. In the simulation, $N = 100$ mobile sensor nodes are initially randomly distributed in a 150m x 150m square field. N mobile sensor nodes contain N_{src} source nodes and a sink node. The maximum range of wireless communication is set to 35m. The batteries of mobile nodes are initially randomly charged in the range $10\ \mathrm{kJ} \sim 150\ \mathrm{kJ}$. It is assumed that the sink node can use the unlimited energy source. The parameter setting used for energy model is as follows: for mobility, we used $k = 2\ \mathrm{J/m}$ as an optimal speed of the node has been discussed in [2,3,4,10]. For transmission, we used $a = 0.6 \times 10^{-7}\ \mathrm{J/bit}$ and $b = 4.0 \times 10^{-10}\ \mathrm{Jm^{-2}/bit}$ as the standard setting which is consistent with the empirical measurements on a CC2420mote [11]. For the reception, we used $c = 1.4 \times 10^{-7}\ \mathrm{J/m}$ [2,3]. The size of data initiated from the source node in one round is referred as the chunk data size m.

In the simulation, we perform the two steps described in the section 3. For the step one, we perform BAIR-D and BMRC-POA for determining the initial route. For the step two, where the optimal position of relaying nodes is determined, we use battery-aware mobile relay algorithm as in [4]. Then, the data is transferred from the source node to

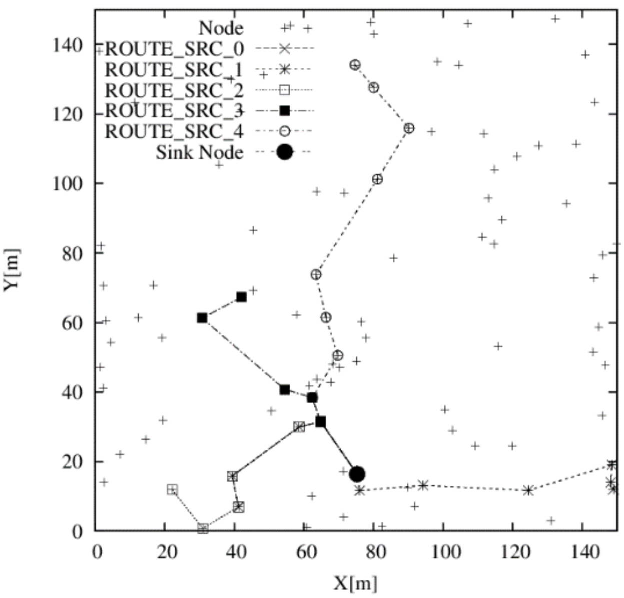


Fig. 5. An example of routes constructed by BAIR-D for 5 source nodes and α = 4.5.

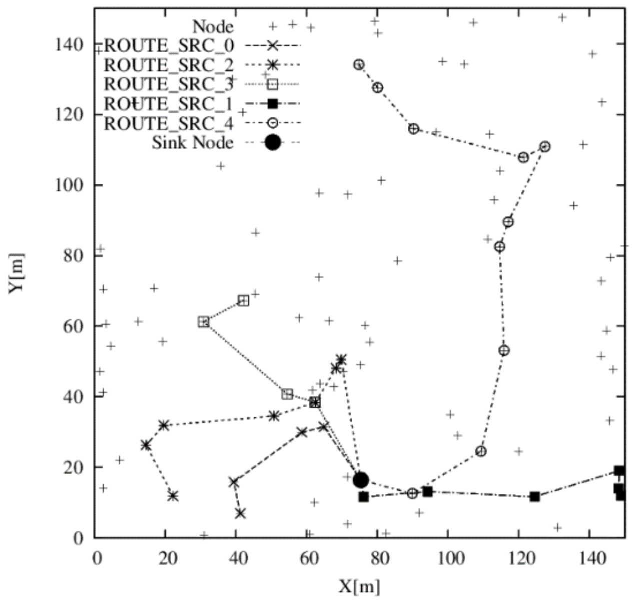


Fig. 7. An example of routes constructed by BMRC-POA for the nearest-first order (5 source nodes and α = 4.5).

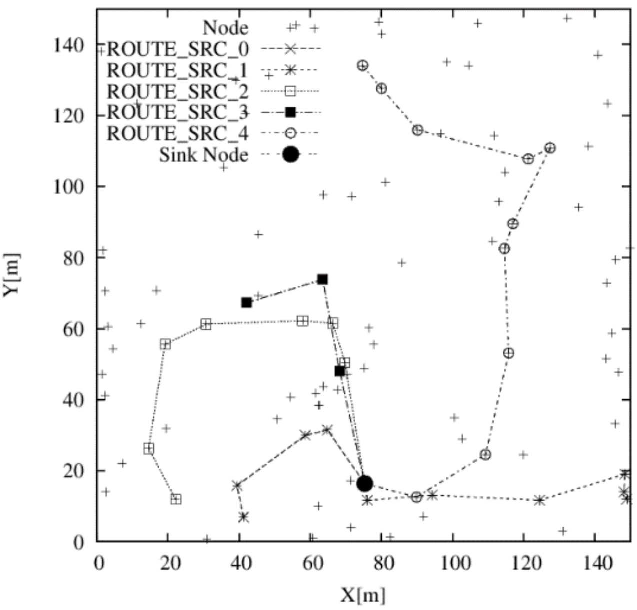


Fig. 6. An example of routes constructed by BMRC-POA for the random order (5 source nodes and α = 4.5)

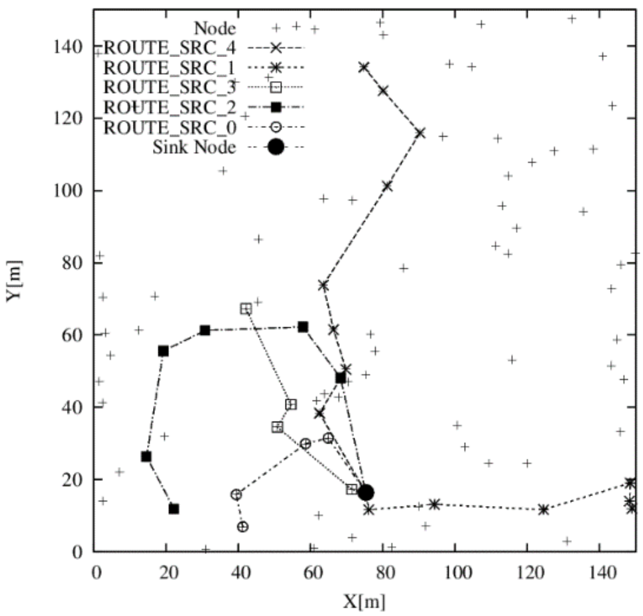


Fig. 8. An example of routes constructed by BMRC-POA for the farthest-first order (5 source nodes and α = 4.5)

the sink node.

In the battery-aware methods, α is used for controlling the balance between distance and battery-level. In the battery-aware methods, BAIR-D, BMRC w/o PO and BMRC-POA, α is an important parameter which controls the balance between the communication cost and the battery level. A larger α makes a longer route from a source to the sink, but avoids nodes with low battery levels. On the other hand, a smaller α makes a shorter route, but fails to avoid nodes with low battery levels. In the following, an effective α = 4.5 found in [6] will be used.

In the first simulation, the initial routes obtained by BAIR-D and BMRC-POA are compared. In this simulation, the routing order for BMRC-POA is random order. Figs. 5 and 6 show the initial routes obtained by BAIR-D and BMRC-POA, respectively. In the initial route obtained by BAIR-D, the source node is allowed to be a member of relaying node to another source node. Therefore, the source node transmits not only its data, but also other data from the other source node. On the other hand, the initial route obtained by BMRC-POA shows that the nodes already used for the initial route of a current node cannot be used as a relaying node to another source node. Each source node only transmits its own data to the sink node.

In the next simulation, we examine the effective routing order of source nodes for BMRC-POA. In Fig. 7, the initial route of BMRC-POA is obtained by the nearest-first order. The routing order for the nearest-first order is source 0,

TABLE I. RESULTS OF SUCCESSFUL RATE
BAIR-D, BMRC W/O PO & BMRC-POA ($\alpha = 4.5$)

# Sources	Successful Rate (%)		
	BAIR-D	BMRC w/o PO	BMRC-POA
1	100	100	100
3	99.6	98.8	99.6
5	99.6	88.2	99.6
7	99.6	64.2	99.6
10	99.6	25.4	99.6
12	99.6	10.6	99.6
15	99.6	1.4	99.6

TABLE II
AVERAGE OF TOTAL COST ($\alpha = 4.5$)

# Sources	Average of Total Cost		
	BAIR-D	BMRC w/o PO	BMRC-POA
1	1.74E-18	1.74E-18	1.74E-18
3	1.95E-18	2.35E-18	2.33E-18
5	2.24E-18	4.97E-18	5.32E-18
7	2.08E-18	6.87E-18	8.20E-18
10	2.02E-18	8.97E-18	1.16E-17
12	1.96E-18	1.36E-17	1.31E-17
15	1.88E-18	1.53E-17	1.36E-17

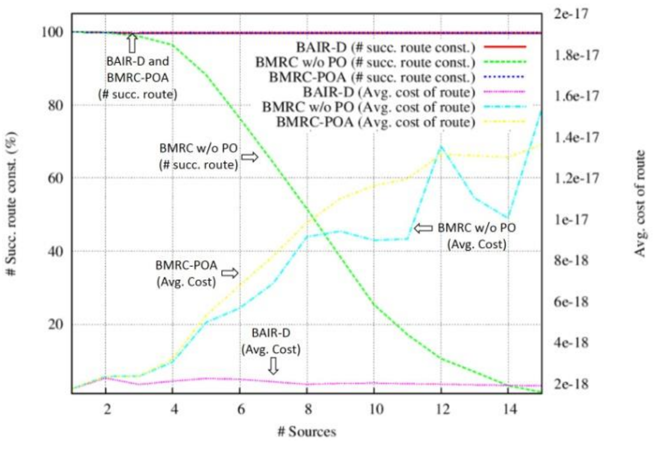


Fig. 9. Successful Rate and Total Cost for BAIR-D, BMRC w/o PO and BMRC-POA ($\alpha = 4.5$)

source 2, source 3, source 1 and source 4. In fig. 8, the initial route of BMRC-POA is obtained by the farthest-first order. The routing order for the farthest-first order is source 4, source 1, source 3, source 2 and source 0. The results in Figs. 7 and 8 show that BMRC-POA still avoid path-overlap to construct the routes.

In the second simulation, the methods are evaluated in terms of the total cost and the successful rate of initial route construction. The total cost means that cost of the successful route construction for every source node. The evaluation values are calculated from 500 runs.

TABLE III. NUMBER OF OPERATING ROUNDS
BAIR-D AND BMRC-POA ($\alpha = 4.5$)

# Sources	# Operating Rounds (chunk data size = 10 MB)	
	BAIR-D	BMRC-POA
1	3800.026	3800.026
3	2232.51004	2778.118474
5	1726.263052	2302.536145
7	1536.572289	1972.965863
10	1325.180723	1570.190763
12	1291.11245	1528.610442
15	1226.801205	1443.064257

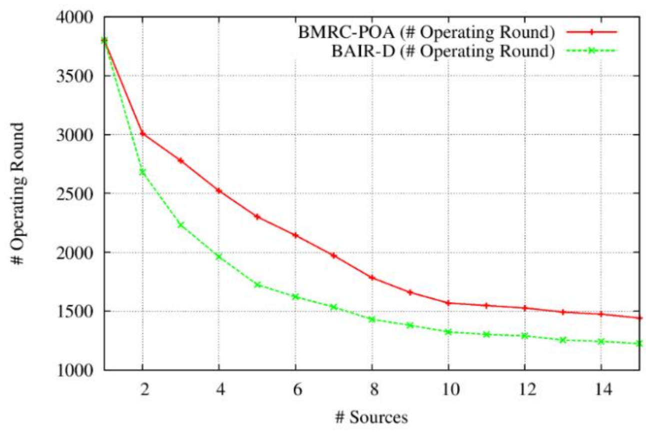


Fig. 10. Number of Operating Rounds BAIR-D and BMRC-POA ($\alpha = 4.5$)

The successful rate is defined by the following equation.

$$\frac{(\#\text{ of runs with successful initial route construction})}{500} \quad (10)$$

In this simulation, in addition to BAIR-D and BMRC-POA, we perform also the strict version of BMRC-POA, which never allows any path overlap. The method, Battery-aware Multiple Route Construction without Path Overlap (BMRC w/o PO), calls the function BAIR-D of (A) in BMRC-POA, but if the route construction for some sources fail then the algorithm terminates as a failed construction.

In our methods, the higher successful rate of route construction is very important, because the sensor nodes send the sensing data through the relaying node (route). If the route construction fails or there is no route, then the source node cannot send the sensing data to the sink node.

According to the results shown in Tables.1 and 2, and Fig.9, we can observe the following tendencies:

(1) The successful rate of BMRC w/o PO rapidly decreases with the number of sources. The degradation is very critical. For example, the rate for $N_{\mathrm{src}} = 10$ is 25.4% and the one for $N_{\mathrm{src}} = 15$ is 1.4%.

(2) Unlike BMRC w/o PO, BMRC-POA achieves the same successful rate as for BAIR-D. Although the successful rate still degrades with the number of sources, the degradation is mild. For $N_{\mathrm{src}} = 15$, the successful rate is 99.6 %.

TABLE IV. SUCCESSFUL RATE OF BMRC-POAFOR THREE TYPES OF ROUTING ORDERS (α = 4.5)

# Sources	Successful Rate (%)		
	Random	Nearest-First	Farthest-First
1	100	100	100
3	99.6	99.6	99.6
5	99.6	99.6	99.6
7	99.6	99.6	99.6
10	99.6	99.6	99.6
12	99.6	99.6	99.6
15	99.6	99.6	99.6

TABLE V. NUMBER OF OPERATING ROUNDS OF BMRC-POA FOR THREE TYPES OF ROUTING ORDERS (α = 4.5)

# Sources	# Operating Rounds (Data size = 10 MB)		
	Random	Nearest-First	Farthest-First
1	3800.026	3800.026	3800.026
3	2778.11847	2803.720884	2806.504016
5	2302.53615	2277.52008	2364.734940
7	1972.96586	1912.46988	2057.475904
10	1570.19076	1543.443775	1646.445783
12	1528.61044	1508.98996	1532.696787
15	1443.06426	1373.837349	1493.196787

(3) In terms of the total cost, BAIR-D is always the best among all the methods. As the number of sources increases, the difference becomes slightly larger.

In this simulation, we also evaluate BMRC-POA in terms of the successful rate of route construction. Table. 4 shows that the successful rates for three types of orders of source nodes are same. The successful rate is 100% for N_{src} = 1. Although the successful rate degrades with N_{src}, the degradation is mild. For example, the rate for N_{src} = 15 is 99.6%.

Next, the methods are evaluated in terms of the number of operating rounds. An operating round means the round where all source nodes successfully transmit the sensed data to the sink. The number of operating rounds is evaluated after when the relaying nodes are placed at the optimal position determined by battery-aware mobile relay algorithm [4]. The evaluation values are calculated from 500 runs.

In Table. 3 and Fig. 10, BAIR-D and BMRC-POA are compared in terms of the number of operating rounds. BMRC-POA achieves approximately 12~33% improvement against BAIR-D for 2 $\leq N_{\text{src}} \leq$ 15. Although the improvement ratio decreases with $N_{\text{src}} \geq 6$, the degradation is mild. For example, the improvement ratio for N_{src} = 12 is 18.4% and the one for N_{src} = 15 is 17.6%.

Finally, three types of orders of source nodes are evaluated in terms of the number of operating rounds. According to the results shown in Table. 5 and Fig. 11, in terms of the number

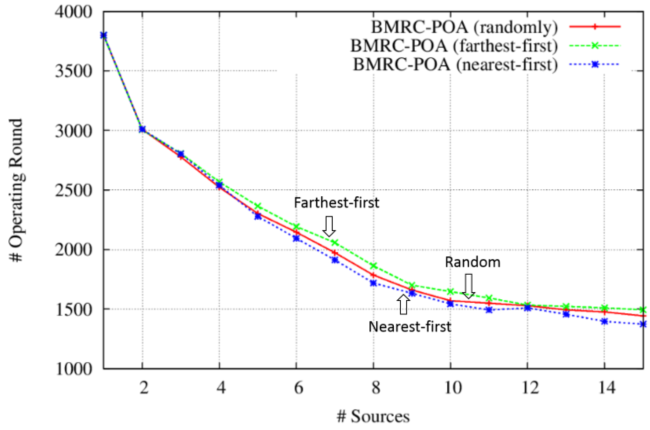


Fig. 11. Number of Operating Rounds of BMRC-POA for Three Types of Routing Orders (α = 4.5).

of operating rounds, the farthest-first order for BMRC-POA is the best among all the routing orders.

The simulation results show that BMRC-POA based on farthest-first order can enhance the network lifetime of WSN.

VII. CONCLUSION

In this paper, we propose battery-aware multiple route construction with path-overlap avoidance (BMRC-POA). The path-overlap increases the energy consumption of the nodes on overlapped paths. This makes the overloaded nodes go quickly down. BMRC-POA avoids the path-overlap as much as possible in the route construction. The simulation result showed that BMRC-POA is more effective than BAIR-D in terms of the number of operating rounds. Therefore, it can prolong the lifetime of sensor nodes.

Further, for BMRC-POA, we consider three types of orders of source nodes in route construction, random order, nearest-first order, and farthest-first order. The simulation results show that the farthest-first order is superior in terms of the number of operating rounds. In the future work, we will consider the refinement of BMRC-POA.

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