World Academy of Science, Engineering and Technology
International Journal of Computer and Information Engineering
Vol:10, No:1, 2016

Improved Network Construction Methods Based on Virtual Rails for Mobile Sensor Network

Noritaka Shigei, Kazuto Matsumoto, Yoshiki Nakashima, Hiromi Miyajima

Open Science Index, Computer and Information Engineering Vol:10, No:1, 2016 publications.waset.org/10003371.pdf

Abstract—Although Mobile Wireless Sensor Networks (MWSNs), which consist of mobile sensor nodes (MSNs), can cover a wide range of observation region by using a small number of sensor nodes, they need to construct a network to collect the sensing data on the base station by moving the MSNs. As an effective method, the network construction method based on Virtual Rails (VRs), which is referred to as VR method, has been proposed. In this paper, we propose two types of effective techniques for the VR method. They can prolong the operation time of the network, which is limited by the battery capabilities of MSNs and the energy consumption of MSNs. The first technique, an effective arrangement of VRs, almost equalizes the number of MSNs belonging to each VR. The second technique, an adaptive movement method of MSNs, takes into account the residual energy of battery. In the simulation, we demonstrate that each technique can improve the network lifetime and the combination of both techniques is the most effective.

Keywords—Wireless sensor network, mobile sensor node, relay of sensing data, virtual rail, residual energy.

I. INTRODUCTION

WIRELESS Sensor Netowrk (WSN) has been used in various applications involving monitoring, surveillance, detection and so on [1]. Introducing mobile nodes into WSN is an attractive approach, because the mobility of nodes can be utilized to improve the WSN's performances [2] such as coverage [3], connectivity [4], reliability [5] and energy efficiency [6]–[8].

For WSN model consisting of static sink node and mobile sensor nodes (MSNs), which is referred to as mobile WSN (MWSN) in this paper, network construction methods have been studied [9]–[11]. Those studies assume that the MSNs are sparsely deployed in an observation region, and they discuss how to effectively construct the network connecting every MSNs with the static sink node. Although a sparse deployment can cover a wide range of field with a small number of sensor nodes, most of sensor nodes at their sensing positions have no communication path to the sink. Therefore, in order to send the sensing data to the sink node, the MSNs need to move so as to construct the network to the sink. In the network construction, it is desired that (1) each node autonomously determines its movement and (2) the total energy consumption by the communication and the locomotion is minimized. Shortest Route (SR) method [9] and the method based on virtual rails [10], which is referred to as VR (Virtual Rail) method, satisfy the requirement (1).

The VR method is simple but effective. The VR method utilizes multiple virtual rails (VRs), which radiate from the sink node. MSNs line up on virtual rails and relay the sensing data from the farther nodes to the sink node. In [10], it has been shown that the VR method outperforms the SR method in terms of energy efficiency. Further, Maeda et.al proposed the enhanced version of VR method, which incorporates an idea of adaptive node movement based on the energy consumption [11]. However, there is room for improvement on the VR method.

In this paper, we propose two types of effective techniques for the VR method. They can prolong the operation time of the network, which is limited by the battery capabilities of MSNs and the energy consumption of MSNs. The first technique, an effective arrangement of VRs, almost equalizes the number of MSNs belonging to each VR. The second technique, an adaptive movement method of MSNs, takes into account the residual energy of battery. In the simulation, we demonstrate that each technique can improve the network lifetime and the combination of both techniques is the most effective.

II. MOBILE WSN MODEL

In the following, the assumptions on mobile WSN (MWSN) model considered in this study are described. The network consists of one static sink node and N mobile sensor nodes (MSNs). The size of observation region is a square of M[m] $\times$ M[m], and the sink node, which is powered by an unlimited energy source, is located at a corner of the square. Every MSNs have to send their sensing data to the sink node. The assumptions on MSNs are as follows: 1) each MSN is powered by a limited energy source such as battery, 2) it can identify its location by an equipped GPS or other system, 3) it equips with a microprocessor used for data processing, 4) it has a radio communication capability where the transmission range is limited within the distance of D_{c}[m] and the transmission power can controlled according to the distance to the target node, and 5) it can move by an equipped electric motor.

The energy consumption model of MSN is as follows. When an MSN 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 an MSN transmits a data of m[bit] over a distance of d[m], it consumes the following energy

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

N. Shigei, Y. Nakashima and H. Miyajima are with the Graduate School of Science and Engineering, Kagoshima University, 1-21-40 Korimoto, Kagoshima, Japan, and K. Matsumoto was with the Graduate School of Science and Engineering, Kagoshima University. e-mail: shigei@eee.kagoshima-u.ac.jp, k2534787@kadai.jp, k4951381@kadai.jp, miya@eee.kagoshima-u.ac.jp

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

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

where the parameter c depends on the radio platform.

The one cycle of the operation of MWSN is as follows: 1) Each MSN performs sensing operation at its observation site for a specific time period, 2) each MSN moves so as to construct the tree-structured network whose root node is the static sink node, 3) starting with the leaf nodes, each MSN forwards its own sensing data and incoming data to the parent node, nearer to the sink node, and 4) each MSN returns to its observation site by the shortest path.

III. CONVENTIONAL NETWORK CONSTRUCTION METHODS

A. Shortest Route Method

In Shortest Route (SR) Method, the base station (BS) node, which also acts as the sink node, leads the network construction process. The network is connected gradually from the BS node to the leaf nodes. At first, the member node in the constructed network is only the BS node. Each MSN moves toward the nearest member node in the network. When an MSN arrives at the communication range of the member node, the MSN node joins the network as a member node. Every a member node is added to the network, the information of the new node is notified to the BS node via the constructed network and then the BS node broadcasts the coordinates of the new member node. The non-member nodes receiving the information determine the new destination, which is the nearest member node.

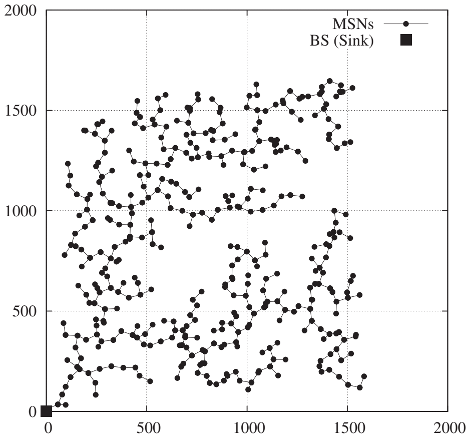


Fig. 1 A network constructed by the SR method

Fig.1 shows an example of the network constructed by the SR method. Initially, the MSNs are uniformly distributed in the square region of size 2000m×2000m. We can observe that 1) farther nodes from the sink node have to move larger distances and 2) the nodes near by the sink node have to relay almost all the sensing data. This observation means that a farther or nearer node incurs a large energy consumption due to locomotion or communication.

B. Ideal Movement Method

Unlike SR method and VR method, the Ideal Movement (IM) method needs the coordinates information of all the MSNs. The movement destination for each MSN is calculated by using all the node informations. Therefore, the method cannot be performed autonomously by the MSNs. For a reasonable implementation, the sink node knows all the MSNs' coordinates, calculates the movement destination for all the MSNs and then broadcasts the movement destinations to all the MSNs.

The IM method determines the movement destination as follows. Let V be the set of all the MSNs. Let P be the set of the member nodes of the constructed network. Let T be the set of the edges in the constructed network. Let Q be the set of the non-member nodes of the constructed network. Initially, let $P \leftarrow \{s\}$, $Q \leftarrow V$ and $T \leftarrow \emptyset$, where s is the sink node. While $Q \neq \emptyset$, the following steps 1)∼4) are repeated. 1) Find the edge $(u_{\min}, v_{\min})$ such that $d(u_{\min}, v_{\min}) = \min_{u \in P, v \in Q} d(u, v)$, where $d(u, v)$ is the distance between nodes u and v. 2) Let $P \leftarrow P \cup \{v_{\min}\}$, $Q \leftarrow Q \setminus \{v_{\min}\}$ and $T \leftarrow T \cup \{(u_{\min}, v_{\min})\}$. 3) Calculate $v_{\min}$'s movement destination that is located the distance D_{c} from $u_{\min}$ and the minimum distance from the original position of $v_{\min}$. 4) Set the coordinates of $v_{\min}$ to the one calculated in 3).

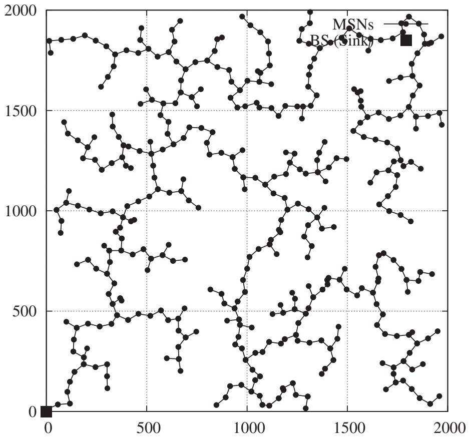


Fig. 2 A network constructed by the IM method

Fig.2 shows an example of the network constructed by the IM method. The initial condition is same as for Fig.1. Unlike the SR method, the MSNs are almost uniformly distributed. However, like the SR method, the nodes near by the sink node have to relay almost all the sensing data. As a result, a nearer node incurs a large energy consumption due to communication.

C. Virtual Rail Method

Likewise the SR method, the Virtual Rail (VR) method can be performed autonomously by the MSNs. In order to achieve it, the VR method utilizes multiple virtual rails, which do not exist in reality and virtually exist. Fig.3 shows the virtual rail

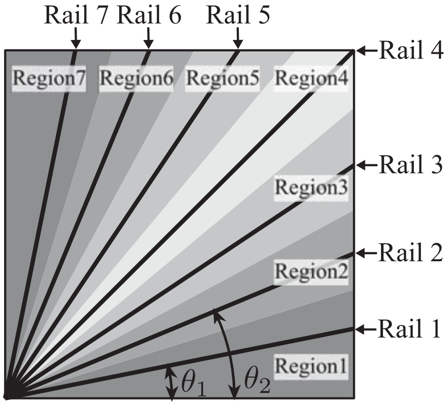


Fig. 3 The virtual rail arrangement of conventional VR method for $R = 7$

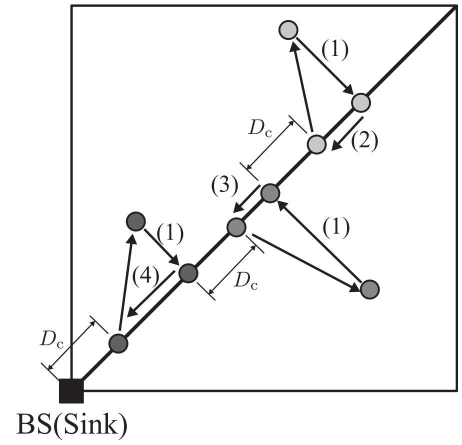


Fig. 4 The nodes' movement in conventional VR method

arrangement for the number of virtual rails $R = 7$. The virtual rails are arranged at equal angle intervals, that is, $\theta_i = i \times \theta_1$ and $(R+1)\theta_1 = \frac{\pi}{2}$, where θ_i is the angle of i-th rail.

The virtual rails are utilized for determining the path and the movement destination for each MSN. Concerning the path determination, each MSN belongs to the nearest rail, that is, every MSNs in region i belong to i-th rail. The nodes belonging to the same rail constitute a single path to the sink. The movement of the MSNs is as follows. 1) Each MSN moves on the shortest path to the rail and stops on the rail. 2) For each rail, starting from the MSN farthest from the sink node, each MSN moves at the position of the distance D_c from the neighboring node located on the sink node side, and the node forwards its own sensing data and incoming data to the neighboring node. Fig.4 shows an example of the node movement for $R = 1$ and $N = 3$. In the figure, the numbers (1)$\sim$(4) indicate the order of moves.

Fig.5 shows an example of the network constructed by the VR method. Unlike SR method and IM method, the VR method reduces the energy consumption of the nodes near by the sink node because they relay only the data of the nodes on the same rail. However, when the virtual rails are arranged at equal angle intervals, the number of nodes belonging to a rail varies for each rail. Some nodes on a rail with a larger number of member nodes tend to go down earlier than the ones on the other rails. Some solutions for this issue are presented in the next section as our proposal.

IV. IMPROVEMENT TECHNIQUES FOR VR METHOD

This section describes two approaches to improve the conventional VR method described in Section III-C. The first approach is to optimizing the rail arrangement, and the other is to aware the residual energy of MSNs.

A. Optimal Virtual Rail Arrangement

Fig.6 shows the area size of each rail for conventional VR method, in which the rails are arranged at equal angle intervals, where the size of the whole observation region is assumed to be 1.0×1.0. When the sensor nodes are distributed uniformly over the observation area, the number of member nodes for each rail is obviously proportional to the area size of the rail.

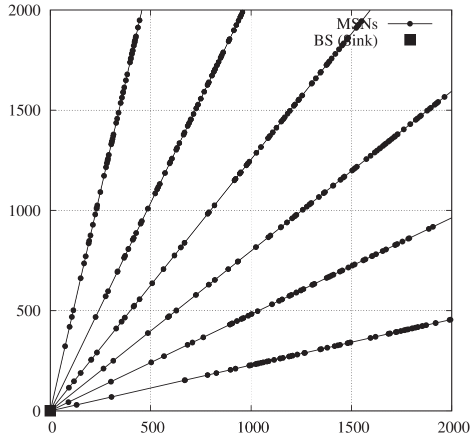


Fig. 5 A network constructed by VR method for $R = 6$

In order to equalize the number of member nodes for each rail, we propose the rail arrangement in which the area size for each rail is identical. The rail arrangement is defined by the angles or the slopes of the rails. Let θ_i and a_i be the angle and the slope of i-th rail ($i \in \{1, 2, \cdots, R\}$), respectively. θ_i and a_i are in the following relation.

$$\theta_i = \arctan(a_i) \tag{4}$$

In the following, the rail arrangement is given for each of odd R and even R cases.

1) For Odd R Case: For odd R case, there exists the rail located on the diagonal line of the observation region. The rail number of the diagonal one is $C = \frac{R+1}{2}$ and its slope is $a_C = 1$. For $i \in \{C+1, C+2, \cdots, R\}$, the following relation holds.

$$\theta_i = \frac{\pi}{2} - \theta_{2C-i} \tag{5}$$

Therefore, in the following, we consider the rails from 1st to C-th. When the areas for every rails are same, the right edge of the observation region is equally divided by the rails. Therefore, for each $j \in \{2, 3, \cdots, C\}$, the following equation

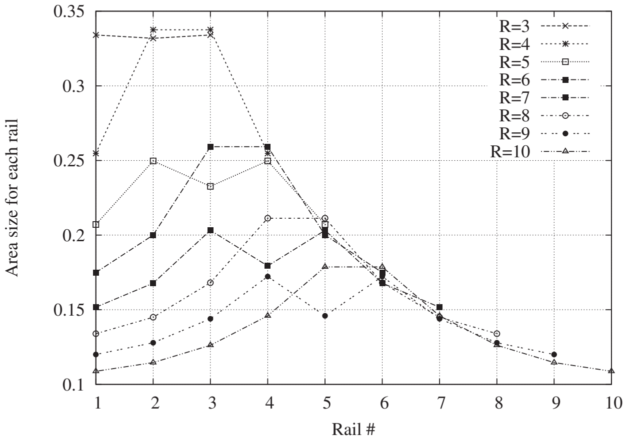


Fig. 6 Area sizes of each rail for conventional VR method

holds.

$$\tan\left(\frac{\arctan(a_j)+\arctan(a_{j-1})}{2}\right)=\frac{2(j-1)}{R} \quad (6)$$

Solving Eq.(6) for $j = C$ with $a_C = 1$, we have the following solution.

$$a_{C-1}=\tan\left(2\cdot\arctan\left(\frac{R-1}{R}\right)-\frac{\pi}{4}\right) \quad (7)$$

Further, solving Eq.(6) for each $j = \{2, 3, \cdots, C-1\}$, we have a_i for $i \in \{1, 2, \cdots, C\}$ as follows:

$$a_i=\begin{cases}\tan\left(2\cdot\arctan\left(\frac{2i}{R}\right)-\arctan(a_{i+1})\right) & 1\le i\le C-1\\ 1 & i=C\end{cases} \quad (8)$$

2) For Even R Case: For even R case, the rail arrangement with equal area sizes is not unique. The rail arrangement depends on a given a_1 satisfying the following condition.

$$0 \le a_1 < \frac{2}{R} \quad (9)$$

The area of each region is $\frac{S}{R}$, where S is the area of the whole observation region. The upper bound of a_1 is derived from this fact. For $i \in \{2, 3, \cdots, \frac{R}{2}\}$, each a_i is determined by the following recurrence relation.

$$a_i=\frac{4(i-1)}{R}-a_{i-1} \quad (10)$$

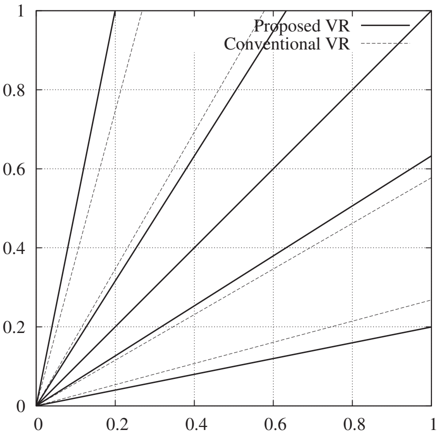
In order to obtain R regions of area $\frac{S}{R}$, a_i should guarantee that the total area of i-th $\sim \frac{R}{2}$-th regions is $\frac{S}{2}\cdot\left(1-\frac{2}{R}(i-1)\right)$. Since the total area of 1st $\sim (i-1)$-th regions is $\frac{a_{i-1}+a_i}{2}\cdot\frac{S}{2}$, the total area of i-th $\sim R/2$-th regions is as follows:

$$\frac{S}{2}-\frac{a_{i-1}+a_i}{2}\cdot\frac{S}{2}. \quad (11)$$

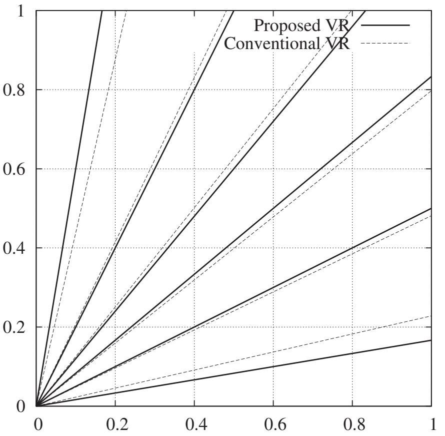
By substituting Eq.(10) into Eq.(11), we can confirm that the total area of i-th $\sim \frac{R}{2}$-th regions is $\frac{S}{2}\cdot\left(1-\frac{2}{R}(i-1)\right)$.

For each $i \in \{\frac{R}{2}+1, \frac{R}{2}+2, \cdots, R\}$, each a_i is determined by using a_{R-i-1} as follows:

$$a_i=\frac{1}{a_{R-i+1}}. \quad (12)$$



(a) For $R = 5$.



(b) For $R = 6$.

Fig. 7 Rail arrangement comparison between proposal and conventional

3) Example of Rail Arrangement: Fig.7 shows examples of rail arrangements by the proposed method and the conventional method for $R = 5$ and $R = 6$. For $R = 6$, $a_1 = 1/R$ is used, which is the best choice as shown in Section V.

for which both sides of 1st rail have a same width. In the figures, a solid line is for the proposed method and a broken line is for the conventional one. For $R = 5$, the 3rd rail, which is the diagonal line, is identical for both methods. We can observe that the proposed VR method decreases the area sizes corresponding to middle rails compared with the conventional VR method.

B. Residual Energy-Aware VR Method

In the conventional VR method, every nodes perform the same operation of movement and communication for every round, where one round means the one cycle of the operation described at the end of section II. This makes some specific nodes with a large energy consumption per round go down quickly. Consequently, the period of time for keeping the maximum of observation coverage is limited.

In order to prolong the period of time for keeping the maximum coverage, we propose a method taking into account the residual energy of MSNs. In the method, each MSN determines its policy for movement and communication according to its residual energy.

For explanation, some notations are introduced. For each MSN $i \in \{1, 2, \cdots, N\}$, let e_i be the residual energy of MSN i and let d_i be the distance between the sink node and MSN i. At each round, each MSN is in Phase 1, 2 or 3 and performs the corresponding operation. The algorithm is shown below.

Algorithm Residual Energy-Aware VR

At the first round, every MSN is in Phase 1.

Phase 1: The MSNs in Phase 1 perform the following operation. Every MSNs perform the same operation as for the conventional VR method. Each MSN $i \in \{1, 2, \cdots, N\}$ memorizes the energy consumption in the first round as $\tilde{e}_i$. From the next round, every MSNs move on Phase 2.

Phase 2: The MSNs in Phase 2 perform the following steps.

(2-1) Move on the shortest path to its own rail and stop on the rail.

(2-2) If MSN i is not the farthest one for the rail, wait for a contact from the neighboring MSN farther from the sink. After getting the contact, receive the data from the contacting MSN. Further, if the following relation holds for MSN i, then move on Phase 3 from the next round and let the contacting MSN know its own phase 3 transition.

$$e_i < \tilde{e}_i \cdot \gamma \cdot \frac{d_i}{\sqrt{2}M}, \tag{13}$$

where $0 \leq \gamma < 1.0$ controls the threshold for moving on phase 3.

(2-3) Let v_{ngb} be the neighboring MSN nearer from the sink.

(2-4) If v_{ngb} is in phase 2, which was notified in the previous round, move at the position of the distance D_{c} from v_{ngb} and then pass its own data to v_{ngb}. Further, receive the information whether v_{ngb} moves on Phase 3 or not in the next round. Go to (2-6). Otherwise, that is, v_{ngb} is in Phase 3, move at the position where v_{ngb} was located in Phase 2, and then receive the data from v_{ngb}. Let v'_{ngb} be v_{ngb}'s neighboring MSN nearer from the sink. Further, receive the information (coordinates and phase) about v'_{ngb}.

(2-5) Let $v_{\mathrm{ngb}} \leftarrow v'_{\mathrm{ngb}}$. Go to (2-4).

(2-6) Return to its own observation site with the shortest path. Renew $e\tilde{}_i$ with the energy consumption in the current round.

Phase 3: The MSNs in Phase 3 perform the following operation. Move on the shortest path to its own rail and stop at the position of the distance D_{c} from the rail. Wait for a contact from the neighboring MSN farther from the sink. After getting the contact, pass the data to the contacting MSN. Return to its own observation site with the shortest path. □

Fig.8 shows the movement in the proposed residual energy-aware VR method.

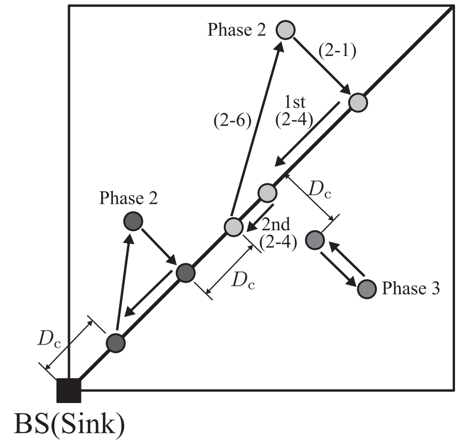


Fig. 8 The nodes' movement in residual energy-aware VR method

TABLE I
The Simulation Parameters

Item	Used value
# MSNs N	400
Communication range D_{c}	60m
Amount of data sensed by an MSN in one round	5Mbit
Initial energy level	10^4J
Observation field size $M \times M$	2000m×2000m
Locomotive param. k	1J/m
Transmission param. a	50nJ/bit
Transmission param. b	0.1nJ/bit·m^2
Reception param. c	50nJ/bit

V. NUMERICAL SIMULATION

In this section, the following three type of proposed methods are compared with conventional VR method, SR method and IM method.

- OVR method: conventional movement with Optimal Virtual Rail (OVR) arrangement
- REA-VR method: Residual Energy-Aware (REA) movement with conventional Virtual Rail (VR) arrangement
- REA-OVR method: Residual Energy-Aware (REA) movement with Optimal Virtual Rail (OVR) arrangement

Since our objective is to improve the period of time for keeping the maximum coverage, the methods are evaluated in terms of the number of operating rounds, in which all the MSNs are alive. That is, when an MSN goes down, the MWSN is considered to stop its operation. Table I summarizes the parameters used in all the simulations. They are same as the ones used in [8], [11].

In the first simulation, the effective value of 1st rail's slope a_1 for the OVR method with even R is investigated. As noted in subsection IV-A, for even R, any a_1 satisfying (9) can be used. Fig.9 shows the number of operating rounds versus a_1 for different even numbers of rails. We can observe that, for any R, $a_1 = \frac{1}{R}$ is the best. $\frac{1}{R}$ is the middle value of the domain $0 \leq a_1 < \frac{2}{R}$. As noted in subsection IV-A3, in this case, both sides of 1st rail have a same width. In the following, we use $a_1 = \frac{1}{R}$ for the OVR method with even R.

In the second simulation, the effective value for the number of rails R is investigated for the conventional VR method and the OVR method. Fig.10 shows the number of operating rounds versus R for the two methods. For both methods, there exists an optimal value for R. For the conventional VR method, $R = 6$ is the best, and for the OVR method, $R = 5$ is the best.

In the third simulation, the effective values for the parameters γ and R are investigated for REA-VR method and REA-

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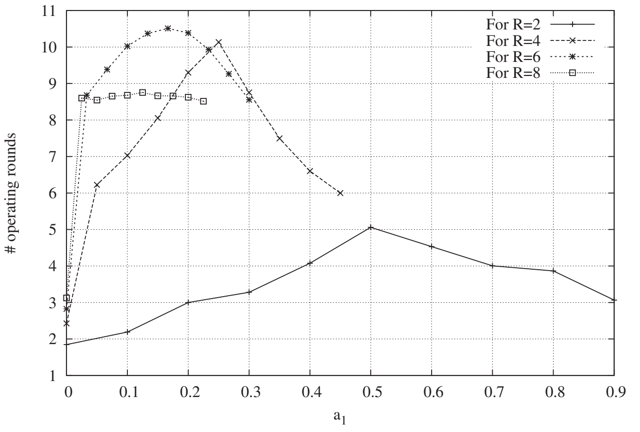

Fig. 9 The number of operating rounds versus 1st rail's angle a_1 in OVR method for even R

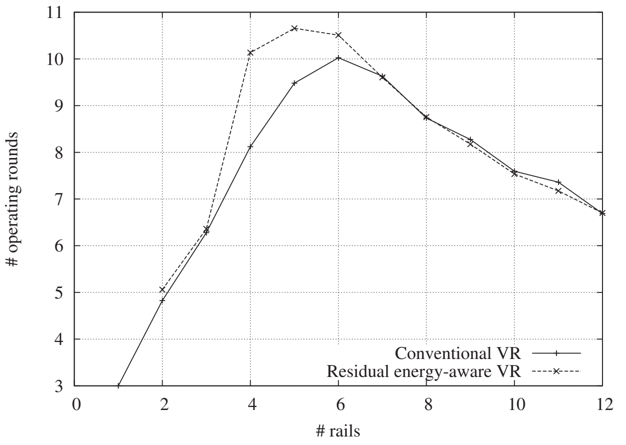

Fig. 10 The number of operating rounds versus R for the conventional VR method and the proposed OVR method

OVR method. Fig.11 shows the number of operating rounds versus the parameter γ for REA-VR method with different numbers of rails. The REA-VR method achieves the best performance for $R = 7$ and $\gamma = 30$. Fig.12 shows the number of operating rounds versus the parameter γ for REA-OVR method with different numbers of rails. The REA-OVR method achieves the best performance for $R = 7$ and $\gamma = 35$.

In the last simulation, three types of the proposed methods and three types of conventional methods are compared. The simulation result is summarized in Table II. Every proposed methods outperform any of the conventional methods. Especially, the proposed residual energy-aware movement improves dramatically the number of the operating rounds. It achieves approximately 50% improvement for both of the conventional rail arrangement and the proposed rail arrangement. Although the improvement degree is not so large, the optimal rail arrangement is still beneficial. It achieves approximately 5%improvement for both of the conventional movement and the residual energy-aware movement.

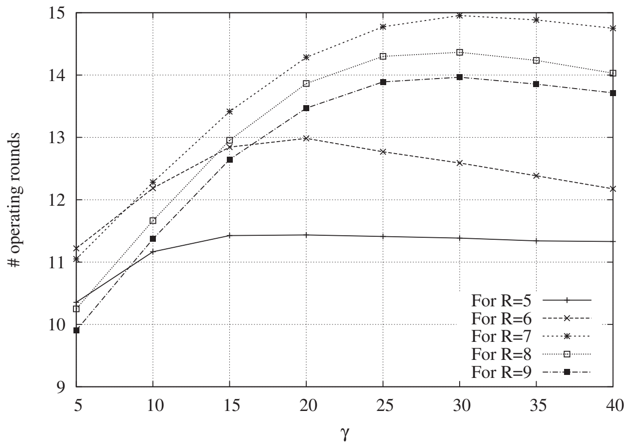

Fig. 11 The number of operating rounds versus the parameter γ for the the proposed REA-VR method

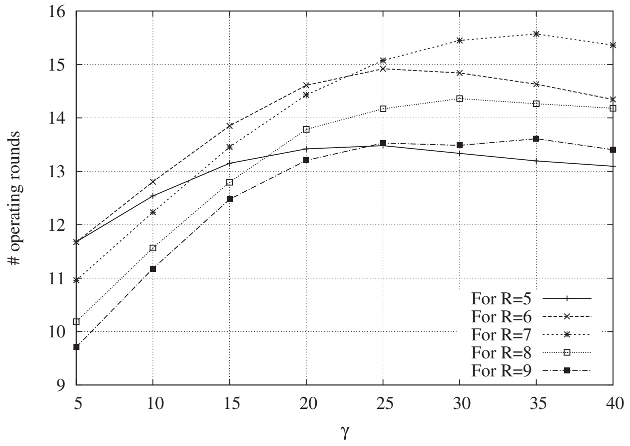

Fig. 12 The number of operating rounds versus the parameter γ for the the proposed REA-OVR method

VI. CONCLUSION

In this paper, we proposed two types of effective techniques for the VR method. The first technique, the optimal arrangement of virtual rails, divides the region into equal-area sub-regions, each of which corresponds to single virtual rail. Its obvious merit is to balance the load around the sink node. The second technique, the residual energy-aware movement, determines each node movement according to the residual energy of battery. The node movement policy restrains the movement of nodes with less residual energy and forces nodes with much residual energy to support the nodes with less

TABLE II
The Number of Operating Rounds for Every Method

Method	# operating rounds	Params.
SR method	7.235	–
IM method	8.585	–
VR method	10.025	$R = 6$
OVR method	10.655	$R = 5$
REA-VR method	14.955	$R = 7$, $\gamma = 30$
REA-OVR method	15.570	$R = 7$, $\gamma = 35$

residual energy. The simulation result demonstrated that, the residual energy-aware movement improves dramatically the number of the operating rounds and the combination of two techniques achieves the best performance.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 26330108.

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Noritaka Shigei received the B.E., M.E., D.E. degrees from Kagoshima University, Japan, in 1992, 1994, and 1997, respectively. He is currently an Associate Professor in Graduate School of Science and Engineering at Kagoshima University. His current research interests include neural network, wireless sensor network, digital communication system, digital circuit design, and parallel computing system.

Kazuto Matsumoto received the B.E. and M.E. degrees from Kagoshima University, Japan, in 2012 and 2014, respectively. From 2012 to 2014, his research interests were in wireless sensor network.

Yoshiki Nakashima received the B.E. degree from Kagoshima University, Japan, in 2015. He is currently a Master course student at Kagoshima University. His research interests include wireless sensor network and communication protocol. He is a student member of IEICE and IEEE.

Hiromi Miyajima received the B.E. degree in electrical engineering from Yamanashi University, Japan, in 1974, and the M.E. and D.E. degrees in electrical and communication engineering from Tohoku University, in 1976 and 1979, respectively. He is currently a Professor in Graduate School of Science and Engineering at Kagoshima University. His current research interests include fuzzy modeling, neural networks, quantum computing, and parallel computing.