Efficient Coverage of Agricultural Field with Mobile Sensors by Predicting Solar Power Generation

Masaru Eto
Nara Institute of Science and Technology, Ikoma, Nara 630–0192, Japan

Ryo Katsuma
Osaka Prefecture University, Sakai, Osaka 599–8531, Japan

Morihiko Tamai
Nara Institute of Science and Technology, Ikoma, Nara 630–0192, Japan

Keiichi Yasumoto
Nara Institute of Science and Technology, Ikoma, Nara 630–0192, Japan

***Abstract*—Wireless sensor networks (WSNs) that periodically collect the environmental information such as temperature, humidity, and so on require the coverage of a given target field any time and the operation lifetime longer than an expected duration by the minimum number of sensor nodes. For these WSNs, we propose a method deciding a schedule of node movement to cover the target agricultural field from plant to harvest by the minimal number of nodes in order to reduce the node deployment cost. The proposed method computes a moving schedule of each mobile sensor node so that all the nodes cover the target field without depleting battery of some of the nodes by predicting solar power generation at each point of the target field where shadow areas change depending on time, orbit of the sun, and height of crops. We conducted computer simulations and compared the performance of the proposed method with a conventional method. As a result, our method achieves 4% reduction of the number of nodes and 10% extension of the operation lifetime compared to the method without estimation of power generation amount.**

I. Introduction

In recent years, wireless sensor networks (WSNs) that consist of many sensor nodes have been widely studied. Data collection WSNs periodically sense environmental data by sensor nodes deployed over the target sensing field and collect the data to a sink through wireless multi hop communication among the nodes. For example, each sensor node on the agricultural field senses environmental information such as temperature, humidity, and so on. We can know whether crops are easy to grow on the field by collecting the sensed data[1], [2], [3], [4]. These applications of WSNs require the coverage of a given target field any time and the operation lifetime longer than an expected duration. The coverage of the field means that the entire field is sensed by sensor nodes.

Some of many studies for efficient coverage of the target field use mobile sensor nodes that are able to move[5], [6]. Mobile nodes are easy to construct WSNs. They also sense the target field by their movement depending on the change of environment, events, and so on. However, energy consumption for movement is large. The movement distance should be shortened in order to extend network lifetime.

As a technique of extending network lifetime, there is energy harvesting[7]. Energy harvesting means that a battery gets electric energy from environmental energy such as sunlight, heat, and so on. However, there is a problem that the amount of generated energy is unstable. In solar energy generation, the amount of generated energy by solar panel depends on the intensity of solar radiation. The intensity of solar radiation is changed by the weather, the orbit of the sun, and the shade by objects. Especially, in agricultural field, crops make the shade region and change it by growth.

In this paper, we target data collection WSNs that periodically collect the environmental information in agricultural field. We propose a method to efficiently cover the field by mobile sensor nodes that are able to charge the energy by solar panel. WSNs are required to operate between the plant of crops and the harvest. Our purpose is to achieve the field coverage and the specified network lifetime T by minimizing the number of nodes in order to reduce the cost for node deployment. We can regard the coverage of mobile nodes as loci of mobile nodes during the duty cycle I (a sink collects the environmental information from all sensor nodes every I minutes). We assume that sensor nodes are able to charge their battery by solar panel, move by equipped wheel and motor, send the data, and receive.

Our method decides the route of each mobile node such that a node with low battery can charge more energy by predicting the amount of solar energy. The prediction is calculated by the position of each node and the time. Then, we calculate the minimal number of nodes that maintain the field coverage more than required duration T.

There are three problems to achieve our goal: (i) how to predict the amount of chargable energy at each point, (ii) how to decide the node movement schedule, and (iii) how to calculate the node schedule. For (i), we estimate shadow areas of the target field by applying growth model of crops. For (ii), we divide the field into grids so that each grid can be covered with one sensor node and compute a moving schedule of all nodes in which at least one node visits each grid in each duty cycle of the WSNs. For (iii), we define small area consisting of some grids and a leader node selected in each small area calculates the schedule to cover the entire small area.

Using the measured values of parameters obtained by the preliminary experiment, we conducted computer simulations and compared the performance of the proposed method with the simple method which does not expect the power generation amount. As a result, the propose method reduce the number of nodes compared to the simple method by 4%. Moreover, the propose method extend the operation lifetime compared to conventional method by 10%.

II. Related Work

In this section, we describe related research on the system for collecting environmental information in agricultural field, which is one of promising applications of WSNs. In these applications, it is necessary to cover the entire target field and to maintain the network for a longer time than the required duration. Thus, we also describe existing research on covering the target field by a WSN and on the energy harvesting technology for extending the WSN lifetime.

A. WSNs in agricultural field

One of major applications of WSN is data collection of environmental information such as temperature and humidity in agricultural field [1], [2], [3], [4].

Mancuso *et al*. deployed a WSN that monitors temperature and relative humidity in a tomatoes greenhouse [1]. These environmental information have influence on to plant growth and it is possible to improve quality of crops by adjusting the temperature and humidity in the greenhouses and the amount of fertilizer.

Langendoen *et al*. constructed a large scale WSN in a potato field to monitor the temperature and humidity [2]. The monitoring of the field allows the farmer to know when the crop is at risk of developing phytophthora.

By deploying static nodes in the target field and monitoring the field from the time for planting to the time for harvesting, the farmer can know the current condition of crop and existence of disease. In these WSNs for data collection, it is required to cover the entire target area constantly to monitor the environmental information of the crop field and to maintain the lifetime of the WSN during the period between the time for planting and the time for harvesting.

B. Methods for covering the target field

There are many studies on covering the target area efficiently with multiple mobile nodes.

Chi *et al*. proposed a method for determining the coverage of the target area where multiple static sensor nodes are deployed. For the sensor network that includes multiple mobile nodes and static nodes, Wang *et al*. proposed a method for determining destination locations of mobile nodes to guarantee k-coverage [5]. WSNs without mobile nodes may have difficulty in adaptation to the environment where the sensing condition varies dynamically. Moreover, because the method proposed in [5] assumes that the mobile nodes can move only once after the deployment, it is difficult to adapt to the changing environment.

Seokhoon *et al*. proposed a relocation method for mobile nodes based on the events occurred in the target sensing area [6]. This method extends coverage of the sensor network to the direction in which the event has occurred by moving mobile nodes while minimizing the energy consumption of the nodes. In this method, however, the energy cost will be increased dramatically because the cost for relocation is not considered.

To solve the problem, it is desirable to determine the relocation schedule of mobile nodes dynamically depending on the changing environment. In addition, it is required to reduce the number of nodes to be used to cover the target field with the consideration on relocation cost for moving the nodes.

C. Energy harvesting in WSNs

To extend the network lifetime, energy harvesting technologies are adopted in several research projects on WSNs [7]. Among them, there are some studies on extending network lifetime by using sensor nodes with solar panels and by taking the orbit of the sun and weather into account.

Gaudett *et al*. proposed a method for covering the target area with the minimum number of nodes by estimating the amount of battery charge for each node based on a time varying solar profile [9]. In this method, the sensing range of each node is automatically adjusted so that the nodes that is holding relatively large amount of the battery in the near future extend their sensing range while the other nodes shrink the range.

Ota *et al*. proposed a network lifetime extension method that estimates the future battery charge for each node based on the weather and lets the nodes that have relatively large amount of residual battery act as relays for data collection [10].

In these existing studies, however, the influence to the battery charge in shady areas is not considered. Because relatively small amount of battery can be charged in shady areas compared with the sunny areas, the nodes that locate in shady areas tend to exhaust their battery.

In this paper, to solve the problems described above, we propose a scheduling method for relocating solar-powered mobile nodes to maintain coverage of the target field over a required period of time with the minimum number of nodes. By considering the influence to the battery charge in shady areas, in our method, the nodes with relatively small amount of battery are moved preferentially to the sunny areas in order to extend the network lifetime.

III. A Problem to Minimize the Deployed Mobile Nodes for Agricultural WSNs

A. WSN model

We target an application periodically collecting the environmental data in agricultural field. In this WSN, many sensor nodes are deployed on the target agricultural field, sense the environmental data every duty cycle I, and send the data to a sink set at the outside of field. Our target WSNs are expected to operate for required duration T (from plant to harvest). A sensor node covers an area with the radius r_s.

B. Energy model

A sensor node can charge its battery by equipped solar panel. The amount of generated energy $Charge(c)$ by the intensity of solar radiation c[MJ/m^2] conforms to Formula (1).

$$Charge(c) = c \times E_{gen} \quad (1)$$

Here, E_{gen} is a constant value representing the energy generation by unit intensity of solar radiation.

A sensor node consumes its energy for moving, data sending, and data receiving.

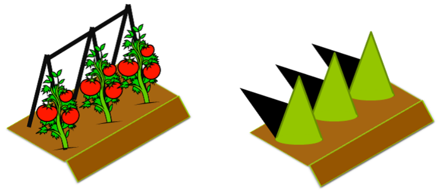


Fig. 1. Model of Crops

Consumed powers $Trans(x, d)$ and $Recep(x)$ required to transmit x[bit] for d[m] and receive x[bit] conform to Formulas (2) and (3), respectively[12].

$$Trans(x, d) = E_{elec} \times x + \varepsilon_{amp} \times x \times d^2 \quad (2)$$

$$Recep(x) = E_{elec} \times x \quad (3)$$

Here, E_{elec} and ε_{amp} are constant values representing the power required by information processing and the power for amplification, respectively.

Consumed power $Sens(D)$ required to sense the environmental information which is D[bit] data conforms to Formula (4).

$$Sens(D) = E_{elec} \times D + E_{sens} \quad (4)$$

Here, E_{sens} is a constant value representing the power for sensing.

Consumed power $Move(d)$ required to move d[m] conforms to Fomula (5)[13].

$$Move(d) = d \times E_{move} \quad (5)$$

Here, E_{move} is a constant value representing the power required to move for 1[m].

C. Sunlight model

Solar power generation depends on the intensity of solar radiation described in Sec. III-B. The intensity of solar radiation is changed by weather and shadow. We denote it in the night, cloudy day, sunny day, and shadowy area of sunny day as $c_{night}(t)$, $c_{cloudy}(t)$, $c_{sunny}(t)$, and $c_{shadowy}(t)$. Here, t represents the time. $c_{night}(t)$ is 0. When it is cloudy day, the intensity of solar radiation is constant value $c_{cloudy}(t)$. When it is sunny day, the intensity of solar radiation is determined by the degree of crop growth and the position of the sun. We assume that crops grow as the shape of cone shown in Fig. 1. The speed of growth follows Formula (6) that is called logistic curve[11].

$$N_t = \frac{K}{1 + (\frac{K}{N_{t-1}} - 1)e^{-n}} \quad (6)$$

Here, N_t, K, and n are the height of crops at the time t, the limit of height, and growth coefficient, respectively.

The position of the sun is determined by latitude, longitude, and time.

D. Problem formulation

Inputs of target problem are a target field $Field$, a set of sensor nodes N, the position of node n at time t $n.pos(t)$, the residual battery amount of node n at time t $n.energy(t)$, r_s, a constant value K, $c_{sunny}(t)$, $c_{shadowy}(t)$, $c_{cloudy}(t)$, E_{gen}, E_{elec}, ε_{amp}, E_{sens}, E_{move}, the expected WSN operation time T, duty cycle I, and the size of sensed environmental data D. Output is the moving schedule of each sensor node. The schedule of node n means $n.pos(t)$ for every time t.

The moving schedule has to satisfy the field coverage. The field coverage can be achieved by a set of mobile nodes visiting to all the points in the field at least once during duty cycle I. This condition is shown as Formula (7).

$$\forall pos \in Field, \exists t \in [t_j, t_j + I), Cover(pos, t) \geq 1 \quad (7)$$

Here, t_j is the start time of each duty cycle $[t_j, t_j + I)$. $Cover(pos, t)$ denotes the number of nodes covering the point pos at time t.

$$\begin{aligned} Cover(pos, t) = \quad & |\{n| \ |n.pos(t) - pos| \\ & \leq n.r \wedge n.energy(t) \\ & > 0 \wedge n \in N\}| \end{aligned} \quad (8)$$

The start time of WSN operation and the time when the field coverage is no longer maintained are denoted by t_{start} and t_{life}, respectively. Let's denote by $Covered(Field, t_j, I)$ a function that becomes true when Formula (7) is satisfied at duty cycle $[t_j, t_j + I)$. Let's suppose $[t_{start}, t_{life})$ can be divided into m cycles. The constraint of maintaining the field coverage conforms to Formula (9).

$$t_{life} - t_{start} > T \wedge \forall j \in \{1, ..., m\} Covered(Field, t_j, I) \quad (9)$$

Sensor node n can cover its sensing region in duty cycle $[t_j, t_j + I)$ if the residual battery amount of n is larger than the energy consumption for sensing, data sending, and data receiving in cycle $[t_j, t_j + I)$. Formula (10) shows this constraint.

$$\begin{aligned} & \forall j \in \{1, ..., m\}, n.energy(t_j) \\ & -Trans(x, d) - Recep(y) - Sens(D) > 0 \end{aligned} \quad (10)$$

Here, the size of sending data, the distance between the sending node and receiving node, the size of received data are denoted by x[bit], d[m], and y[bit], respectively.

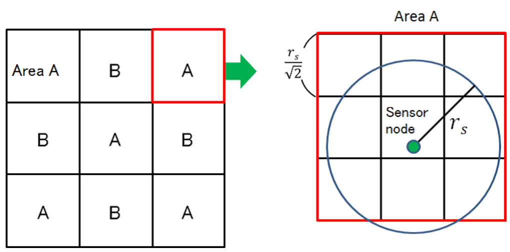
If node n moves in timeslot $[t_j, t_j + I)$, the residual battery amount of n should be larger than the energy consumed for moving. Formula (11) shows this constraint.

$$\forall j \in \{1, ..., m\}, n.energy(t_j) - Move(l) > 0 \quad (11)$$

Here, the moving distance is $l = n.pos(t_j + I) - n.pos(t_j)$.

Our purpose is to determine the node movement schedule minimizing the number of deployed nodes. The objective function is shown in Formula (12).

$$\text{minimize } |N| \text{ subject to } (9), (10) \text{ and } (11) \quad (12)$$



(a) Division into areas (b) Division into grids

Fig. 2. Division of Target Field

IV. Node Move Schedule by Residual Battery Amount Prediction

A. Overview

This section describes our proposed algorithm to solve the number of nodes minimization problem which we defined in Sect. III. The goal of the algorithm is to achieve the WSN lifetime more than the required duration T with the minimum number of mobile nodes. Our proposed algorithm periodically predicts the residual battery amount of each node at the end of the period, and makes a schedule of nodes movement in the period so that the minimum residual battery amount among all the nodes is maximized.

To make our proposed method scalable, the proposed algorithm solves the problem in a distributed manner. First, the entire field is divided into multiple lattice-like *areas* with the fixed sides. By covering each area independently of the others, the entire field is covered. However, calculating nodes move schedule for each area independently will likely results in the *border problem* where nodes near the border are scheduled to move inconsistently (e.g., some node is requested to move to different positions at the same time).

To avoid the border problem, we adopt a method which we proposed in [14] to compute schedules of neighboring areas at different timings. For example, as shown in Fig. 2(a), the entire field is divided into areas and the areas are labeled with A or B so that the neighboring areas do not have the same label. Our algorithm first determines the schedule of areas with label A, then does the schedule of areas with B taking into account the nodes move in the schedules of A areas.

To keep the WSN lifetime over a required duration, in each duty cycle, the node with the maximum residual battery in a area is selected as the *leader node* which computes the move schedule of all nodes in the area to cover the area.

We say that the *WSN lifetime* is the time when the coverage of some area is no longer be achieved with any move schedule. Our proposed method derives the WSN lifetime for different number of nodes, and derives the minimum number of nodes to achieve the WSN lifetime more than the required duration.

Below, we describe the details of our algorithm including the coverage method of the target field, and the prediction method of residual battery amount.

B. Covering the target field

In the target WSN, the entire field must always be covered. As addressed in Sect. III-D, we assume that the entire field is covered if each point in the field is sensed at least once in each duty cycle of period I.

Based on this assumption, each area is divided into smaller square called *grids*, as shown in Fig. 2(b). Here, The side length of the grid is set to $\frac{r_s}{\sqrt{2}}$ where r_s is the sensing radius of sensor nodes. This division guarantees that sensing at any point in the grid covers the entire grid. Therefore, if there is at least one node in a grid at some point of time in each duty cycle, the grid is said to be *covered* in the duty cycle. So forth, in a duty cycle, if each of grids in an area of Fig. 2(b) is covered, the area is said to be *covered*. The proposed algorithm computes a nodes move schedule which covers each area of the entire field based on the above conditions.

C. Predicting residual battery amount

At the beginning of each duty cycle, t_j, each node predicts energy consumption and energy generation during the duty cycle. Then, it computes two cases of the expected residual battery amount at time $t_j + I$: the case when the node stays at the current grid; and the case when it moves to another grid. The computed values are used as parameters when determining the nodes move schedule described in Sect. IV-D.

1) Energy consumption prediction: Our algorithm uses the power consumption model defined in Sect. III-B to calculate energy consumption for sensing, communication, and standby during a duty cycle from time t_j to $t_j + I$. When a node moves, energy consumption for the move is added according to formula (5).

2) Energy generation prediction: Each node predicts the energy generation amounts during the current duty cycle (t_j to $t_j + I$) from the destination position (or the current position when no move). From the past history of solar radiation amount [15], we denote the amounts of global solar radiation and diffuse solar radiation in sunny days by $c_{sunny}(t)$ and $c_{shadowy}(t)$, respectively, and the amount of global solar radiation in cloudy days by $c_{cloudy}(t)$. Here, t is time. In addition, from crop growth and solar orbit, each node predicts whther the current position is sunny or cloudy. $a_{sunny}(t) = 1$, $a_{shadowy}(t) = 1$, $a_{cloudy}(t) = 1$, and $a_{night}(t) = 1$ denote the node's prediction, that is, sunny, shadowy, cloudy, or night at time t. From the obtained amount of solar radiation and the performance of the solar panel used, the energy generation amount at cycle $h_j = [t_j, t_j + I]$ is calculated by formula (13).

$$\begin{aligned} Charge(h_j) &= E_{gen} \times \int_{t_j}^{t_j+I} (c_{sunny}(t) \times a_{sunny}(t) \\ &+ c_{shadowy}(t) \times a_{shadowy}(t) \\ &+ c_{cloudy}(t) \times a_{cloudy}(t) \\ &+ c_{night}(t) \times a_{night}(t))dt \end{aligned} \tag{13}$$

D. Algothm for calculating move schedule

The proposed algorithm first selects a leader node for each area at the beginning of each duty cycle, then the leader node calculates a move schedule to cover the area so that the entire field is covered.

As addressed in Sect. IV-B, the entire field is divided into grids according to the sensing radius r_s as shown in Fig. 4.

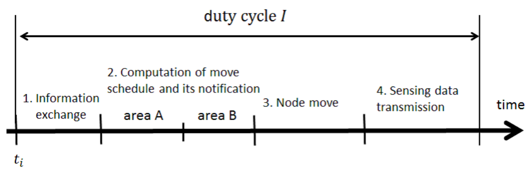


Fig. 3. Flow of actions by each node in each duty cycle

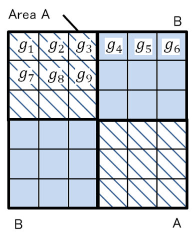


Fig. 4. Example of dividing the entire field

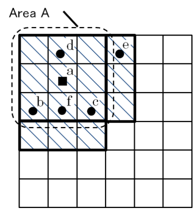
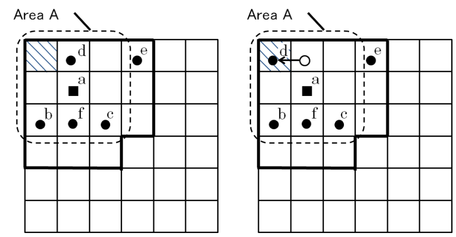


Fig. 5. Grids considered by an area



(a) before move (b) after move

Fig. 6. Example of move schedule

TABLE I. Expected residual battery in Fig. 6

	(a)		(b)
	no move expected battery	move expected battery	expected residual battery
node a	60%	55%	60%
node b	55%	50%	55%
node c	50%	35%	50%
node d	55%	60%	60%
node e	50%	45%	50%
node f	50%	45%	50%

All the grids are uniquely labeled like g_1, g_2, g_3, g_4, ... Then, areas are determined so that each area contains several grids. Each area is labeled with A or B so that neighboring areas do not have the same label.

Fig. 3 shows what actions each node performs in each duty cycle. The details of these actions are described below.

Each node broadcasts information consisting of its current residual battery amount, the expected residual battery amount at time $t_j + I$, and its current location.

Our proposed algorithm for computing a move schedule is shown below.

1) A node with the most residual battery in the area is selected as a leader node.
2) The leader node receives information from all nodes in the area and confirms the unsensed grids in the area which is not occupied by any of the nodes.
3) The leader node calculates the expected residual battery of each node at the end of the current duty cycle $t_j + I$ when the node moves to each of the unsensed grids, and determines the pair of the node and the grid which maximizes the minimum residual battery among all the nodes in the area.
4) the WSN operation is terminated if there is no node which can move to an unsensed grid due to battery shortage, that is, the coverage of the area is no longer possible.
5) when all the unsensed grids are covered, the leader node informs each node of the computed move schedule.

To cover the entire field until the required time T, the algorithm computes a move schedule so that each area is covered, that is, the entire field is covered during the period with length I at each duty cycle. To reflect the result of neighboring areas, move schedules of neighboring areas are computed alternately. As shown in Fig. 3, move schedules are computed for areas with label A first, then those for areas with label B are computed.

The leader node selected in each area computes a move schedule of nodes in the area to which it belongs as well as its neighboring areas. For example, the area A in the left-up corner in Fig. 4 is covered by moving the nodes in the shadowed grids in Fig. 5. To avoid the case that multiple A areas try to move the same node differently, the A area with smaller area ID is given higher priority. When the leader node in area A broadcasts the result, nodes in the neighbor areas can receive it. Then, the leader node in area B uses this information at step (2).

In Fig. 6(a), all nodes a,b,c,d,f in area A collect their position and residual battery with each other. The node with the most residual battery is selected as the leader node. Here, suppose that node a is selected as the leader node.

The leader node a first collects information of nodes in the shadowed grids in Fig. 5. Then, the node a confirms that grids g_1,g_3,g_7, and g_9 are not sensed from the position information of the nodes.

Then, the node a computes amounts of expected residual battery and generated energy at the end of the current duty cycle for each case of a node moving to a grid. Then, node a selects a pair of a node and a grid which maximizes the minimum expected residual battery among the nodes after the move. For example, residual battery amounts of cases that each node stays in the current grid and moves to another unsensed grid g_1 as shown in Table I(a). Here, the reason why the residual battery when node d moves is greater than when it stays in the same grid is that the current grid is shadowy and does not generate so much energy, but the grid g_1 generates larger energy. When either node a, b or d moves, the minimum residual battery becomes 50%. When node d moves, the sum of residual battery of all nodes becomes the largest. Thus, the node a determines that node d moves to grid g_1. Then, as shown in Table I(b), Supposing that node d already finishes move to g_1, the node a computes the move schedule for other unsensed grids in a similar way.

Each node moves according to the schedule informed by the leader node. While the node passes through each grid, it performs sensing at the grid.

After each node finishes its move, it sends the sensed data to the leader node. After the leader node receives the data from

TABLE II. PARAMETER SETTINGS IN THE SIMULATION

Size of target field	$100 \times 100\ m^2$ and $200 \times 200\ m^2$
Sensing radius	30 m
Operation period T	90 days
Sensing interval I	15 min
Battery voltage	2.4 V
Battery capacity	1000 mAh
Power consumption coefficient for data processing E_{elec}	50 nJ/bit
Power consumption coefficient for signal amplification ϵ_{amp}	100 pJ/bit/m^2
Power consumption coefficient for sensing E_{sens}	0.018 J/bit
Wireless method	802.11a
Routing protocol	AODV
Propagation model	TwoRayGround

TABLE III. POWER GENERATION AMOUNT BY THE SOLAR BATTERY CHARGER (THE AVERAGE VALUE AMONG TEN MEASUREMENTS)

Sunny area	180 mW
Shady area	24 mW

all the nodes in the area, it aggregates the data and sends the aggregated data to the sink.

V. EVALUATION

To evaluate our scheduling method, we conducted an experiment using a commercial network simulator, called *Scenargie* [17]. In the experiment, we investigate the required number of nodes of a WSN to cover the target field during a specific period of time using the proposed method and compare the results to the other method (called *simple method* hereafter) that do not consider the power generation amount by sunlight. To determine the parameters to be used in the simulation, we conducted a preliminary experiment with a real solar-powered mobile node to measure the power generation amount by a solar panel and the amount of energy consumption for moving a mobile node.

A. Preliminary experiment

1) Power generation amount by sunlight: As shown in Fig. 7, we built a solar battery charger that uses MPPT (Maximum Power Point Tracking) circuit and two AA size batteries as the secondary battery. The size of the solar panel is 104 mm $\times$ 48 mm.

We measured the power generation amount in a sunny area and a shady area in fine weather. We calculated the average value among ten measurements for each area, and for the shady area the measurement is conducted at the location where a shadow of a plant exists. The results are shown in Table III.

The results show that the power generation amount in the shady area is about 13% of that in the sunny area. We found that the power generation amount depends on the degree of the shadow and the amount drops almost to zero when the area is covered by the shadow completely. Although it implies that it is difficult to accurately estimate the amount of battery to be charged in shady areas, we use the average value shown in Table III in the simulation. Because a cloud is one of object making the shadowy area, we also use the value of the power generation amount in the shady area as the power generation amount on a cloudy and rainy day.

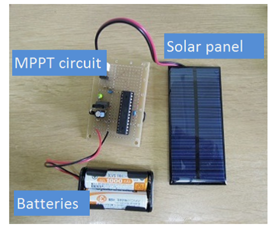


Fig. 7. Solar battery charger

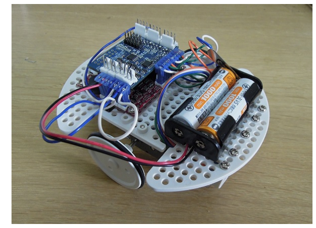


Fig. 8. Mobile node

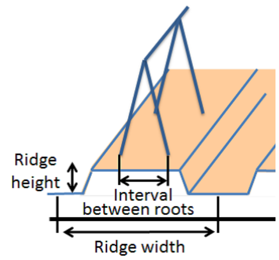


Fig. 9. A ridge in the crop field

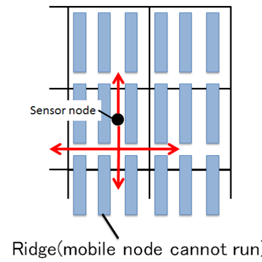


Fig. 10. Node movement in the crop field

2) Battery consumption of driving mechanism: As shown in Fig. 8, we used a Beauto Rover manufactured by Vstone Co., Ltd. [16] for the measurement of the energy consumption of the driving mechanism of the mobile node. The moving speed is adjusted at 50 cm/sec. The electric current during the driving is measured and the amount of the electricity consumption is calculated. Note that for the measurement of the electric current, the steady-state electric current is measured during direct advance traveling. By this experiment, we found that when the speed is at 50 cm/sec, the electricity consumption is 1680 mW.

Because a relatively large amount of the energy is consumed during traveling compared with that during standby, it is important to move mobile nodes efficiently by taking their energy consumption into account.

B. Settings in simulation

In the simulation, by referring to the experiment using real devices in a tomato field [1], we assume that the temperature and humidity in a crop field are collected using a WSN. The purpose of our method is to find the required number of mobile nodes and their relocation schedule to cover the target field during a specific period of time. Table II shows the simulation parameters. We set the operation period of the WSN to 90 days that start from May 1st. We use the weather data of Nara city in 2012[18]. According to Sect. IV-B, the length of a side of a square in the grid is calculated as $30/\sqrt{2} = 21.2$ meter, we set it to 20 meter for simplicity. As described in Sect. V-A, two AA size batteries are used as the secondary battery. The power generation amount by sunlight and the energy consumed by traveling are set to the same values obtained in the preliminary experiment in Sect. V-A.

In the crop field, mobile nodes can move along a path that is not blocked by ridges. As shown in Fig. 9, the target field used in the simulation is a tomato field and has ridges that run in a north and south direction. Each ridge has a width of 120 cm and a height of 20 cm, and the length of the interval

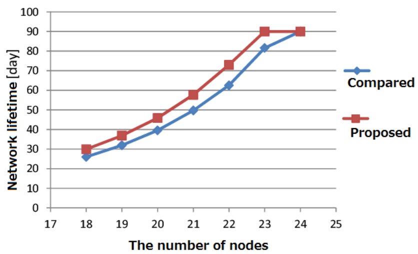


Fig. 11. Network lifetime (field size is 100 $\times$ 100 m^2)

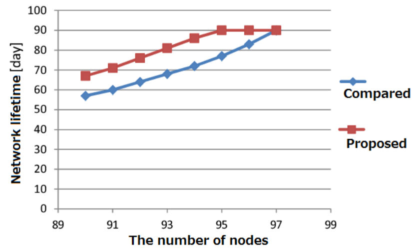


Fig. 12. Network lifetime (field size is 200 $\times$ 200 m^2)

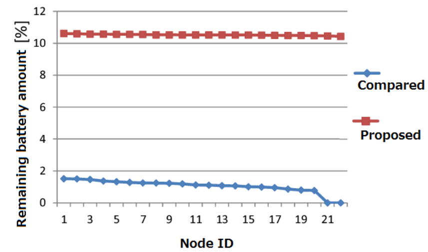


Fig. 13. Remaining amount of battery when the number of nodes is 23 and field size is 100 $\times$ 100 m^2

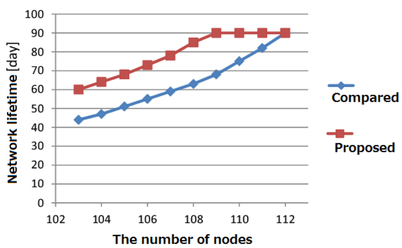


Fig. 14. Network lifetime (sensing interval I is 10 min)

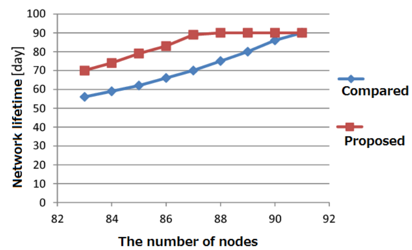


Fig. 15. Network lifetime (sensing interval I is 20 min)

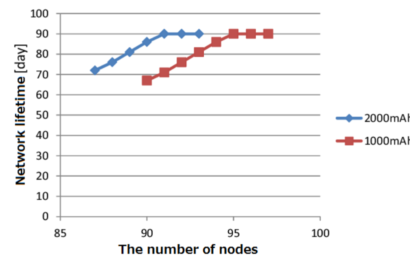


Fig. 16. Network lifetime (battery capacity is varied)

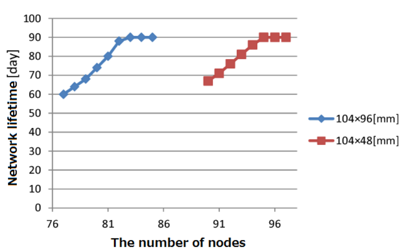


Fig. 17. Network lifetime (size of the solar panel is varied)

between the roots of a growing plant is set to 50 cm. We also assume that the length of each ridge is less than a length of a side of a square in the grid. Mobile nodes can move between adjacent north and south squares with the shortest distance and move between adjacent east and west squares along with a detour route that avoids ridges or a direct route.

C. Results

In this subsection, we describe the simulation results. The network lifetime of the WSN is evaluated while varying the number of mobile nodes. The network lifetime is measured as the number of days in a period from the start time of the operation to the time when the coverage of the target filed breaks down.

We compare the proposed method with the simple method, which does not consider the power generation amount by sunlight. In the simple method, to determine nodes that are moved to the uncovered squares, the remaining battery amount for each node is estimated by considering only the energy consumed by traveling. Then, the relocation schedule is calculated so that the minimum value of the estimated remaining battery among nodes is maximized.

TABLE IV. AVERAGE POWER GENERATION AMOUNT PER DAY WHEN THE NUMBER OF NODES IS 23

Proposed method	3271972 mW
Simple method	3145530 mW

We conducted ten measurements with different random seeds for both the proposed method and the simple method, and calculated the average values among ten measurements for each method.

1) Comparison between different field sizes: Fig. 11 and Fig. 12 show the results of the simulation with the field size of 100 $\times$ 100 m^2 and 200 $\times$ 200 m^2, respectively. Fig. 13 shows the remaining amount of the battery after the operation of WSN when the number of nodes is 23, and Table IV shows the power generation amount per node in a day.

When the field size is 100 $\times$ 100 m^2, at least 23 nodes are required to maintain the coverage of the field for 90 days in the proposed method while the simple method requires at least 24 nodes. Similarly, when the field size is 200 $\times$ 200 m^2, to maintain the coverage for 90 days, at least 95 nodes are required in the proposed method, while the simple method requires at least 97 nodes. From these results, we can say that the proposed method can reduce the number of required nodes 4% and 2% for the field size of 100 $\times$ 100 m^2 and 200 $\times$ 200 m^2, respectively, compared to the simple method. If we use the same number of nodes for both methods, the proposed method can extend the network lifetime up to 16% and 10% on average compared to the simple method. We can see that the remaining amount of the battery in the proposed method is almost the same among the nodes after the operation, while in the simple method, some specific nodes consume larger amount of battery than the other nodes. Moreover, the average value of the amount of energy charged per day in the proposed method is about 4% higher than that of the simple method.

2) Comparison among different sensing intervals: The simulation results when the sensing interval I is 10 min and 20 min are shown in Fig. 14 and Fig. 15, respectively. Here, the field size is set to 200 × 200 m^2. When the sensing interval is 10 min, the proposed method requires at least 109 nodes to maintain coverage for 90 days while the simple method requires at least 112 nodes. Similarly, when the sensing interval is 20 min, the proposed method requires at least 88 nodes while the simple method requires at least 91 nodes. From these results, we can say that the required number of nodes varies depending on the sensing interval, but they have the similar tendency among the different sensing intervals.

3) Influence of battery capacity and size of solar panel: For the proposed method, we also show the results when the battery capacity and the power generation amount with the solar panel are varied. We use the same settings as in Table II and the result is shown in Fig. 16 when the battery capacity is set to 2000 mAh. In addition, the Fig. 17 shows the result when the size of the solar panel is twice as large as that in the previous simulation, assuming that the power generation amount with the solar panel increases proportionally to its size.

When the battery capacity is doubled, we can see that the number of nodes required to maintain coverage for 90 days is reduced by 4. We can also see that when the power generation amount is doubled, the number of nodes is reduced by 12.

D. Discussion

The network lifetime is extended 10% on average in the proposed method compared to the simple method, and the result confirms effectiveness of the proposed method. The reason is that the workload is distributed among nodes in the proposed method, which calculates the relocation schedule of nodes by taking the power generation amount into account, and that the power generation amount per day can be increased by moving nodes to the sunny areas. However, the reduction rate in the number of nodes is not so high compared with the degree of extension in the network lifetime. This is because the increased amount of the power generation by the solar panel is relatively small and this amount can not compensate the increased amount of the energy consumed by the nodes that travel to the uncovered locations, which are occurred due to the reduced number of nodes, for each sensing interval.

We can also find that the number of required nodes to maintain coverage can be reduced by increasing the power generation amount of the solar panel, and this reduction rate is higher than that when the battery capacity is increased. This is because the total amount of power generation during the operation is larger than the battery capacity.

VI. Conclusion

In this paper, we formulated a problem of covering the agricultural field by mobile sensor nodes that can charge their battery by solar energy generation. For this problem, we proposed a method to decide the moving schedule of mobile nodes by predicting the amount of solar energy. Our method maximizes the battery of a node that has the lowest battery amount.

Through computer simulations by network simulator Scenargie, we confirmed that our method reduced the number of nodes required to WSN operation for required duration by 4% and improved the network lifetime by about 10% compared with a method which does not expect the power generation amount.

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